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THESIS

The Effect of Flow Rate and Canister Geometry on the Effectiveness of Removing Carbon Dioxide with Soda Lime

by

Richard Steven Ploss

September 1980

Thesis Advisor: P.F.PUCCI

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The Effect of Flow Rate and Canister Geometry on the Effectiveness of Removing Carbon Dioxide with Soda Lime

by

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Lieutenant Commander, United States Navy
B.S., United States Military Academy, 1969

Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

A continuation of experiments initiated by Commander Calvin G. Miller, USN, on the effect of flow rate, flow geometry and environment temperature on the effectiveness of a commercial soda lime, Sodasorb, to absorb carbon dioxide from a mixture of carbon dioxide and air is described. Modifications to cylindrical four-inch inside-diameter canisters with three length-to-diameter ratios of 1.225, 1.60 and 2.125 were tested. These modifications were in the form of one-half inch axial spacers or annular rings located within the soda lime bed. Steady flow rates of approximately 1, 2 and 3 SCFM of saturated air at one atmosphere and environment temperatures of 40°F, 55°F and 70°F were used. Temperature and pressure distributions through the soda lime bed were measured. The regenerative properties of the soda lime were tested for a length-to-diameter ratio of 2.125, a flow rate of approximately 2 SCFM and an environment temperature of 70°F.

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NOMENCLATURE

English Letter Symbols

A_c	Canister cross-sectional area.
B	Constant in Elam's equation.
D	Inside diameter of the canister.
f	Dimensionless Fanning friction factor for a porous media.
$\sqrt{k}$	Characteristic flow dimension. (.004 inches for Sodasorb - reference [3].)
L	Length of the Sodasorb bed in the canister.
$\dot{m}$	Mass flow rate.
P	Pressure.
Q	Volumetric flow rate.
R	Gas constant.
Re	Reynolds number.
$t_{1/2}$	Time to reach 0.5% carbon dioxide by volume in the exhaust gas of the canister. A measure of the absorbent's effectiveness.
V_c	Macroscopic, superficial, filtration velocity of a porous media.
x	Distance measured from the incoming gas screen along the length of the canister.

Greek Letter Symbols

Δ	Difference or change.
μ	Fluid viscosity.
ρ	Fluid density.

Subscripts

atm Local atmosphere.

c Canister.

f Flowmeter.

L Length of the Sodasorb bed.

s Standard (temperature and pressure).

1 Conditions immediately upstream of the entrance screen to the Sodasorb bed.

2 Conditions immediately downstream of the entrance screen to the Sodasorb bed.

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I. INTRODUCTION

U.S. Navy depth limits for air diving without a diving medical officer and a recompression chamber required on scene is 170 feet [1][1]. The normal working limit is 190 feet, with the maximum allowable depth of 250 feet. Actual bottom time at these depths, compared to the total length of dive, is short; 40 minutes bottom time at 190 feet requires a total dive time of 143 minutes [1].

For deeper dives, all divers breathe "mixed gases" composed of either: nitrogen and oxygen (proportions other than atmosphere), 100% oxygen, or other combination of inert gases and oxygen [1]. Without recirculation of the diver's exhaled air, these expensive gases are normally exhausted to the atmosphere. For a given quantity of diving air, recirculation of a diver's exhaled air permits longer and deeper dives at lower costs.

At the present time, the primary carbon dioxide scrubbing medium utilized in most U.S. Navy self-contained dives is a sode lime produced by W. R. Grace Co., under the registered trademark of Sodasorb [2]. A better understanding of Sodasorb absorptive characteristics for various canister configurations may prove significant to the advancement of the state-of-the-art in today's deep sea diving.

---

[1]Numbers in brackets refer to items in the bibliography.

Miller [3] conducted experiments on the effectiveness of Sodasorb as a scrubbing agent. He tested three cylindrical, four-inch inside-diameter canisters with length-to-diameter ratios of 1.225, 1.60 and 2.125, and for three steady flow rates of approximately 1, 2 and 3 SCFM. The canisters were submerged horizontally in a constant-temperature water bath held at three levels: $40^{o}F$, $55^{o}F$ and $70^{o}F$. Three inlet carbon dioxide fractions of 4.0, 6.0 and 8.0 percent by volume were used. The tests were conducted at a pressure of one atmosphere. The choices of flow rates, geometries, fractions of carbon dioxide, and temperature ranges were selected to correspond to those experienced in actual diving operations.

This report documents the continuation of experimentation with steady flow rates through Sodasorb at a pressure of one atmosphere. The investigation was continued using the same canister configurations, water bath temperatures and air flow rates as Miller. Only one inlet carbon dioxide fraction of 6.0 percent by volume was used.

Miller [3] defines absorption effectiveness as "the time a given absorption system operates before the exit carbon dioxide reaches one-half percent by volume." That definition will be used in this report. The terms "absorption efficiency" and "efficiency" appearing in the references have the same meaning as "effectiveness" does in this report.

Channelling is the preferential flow of gas through a media due to non-uniform resistance to flow. Channelling will occur whenever the material granules are unable to interlock with one another in a uniform manner. It has been demonstrated that in the controlled environment of anesthesiology, channelling along the interface between the Sodasorb and the canister walls does occur and that the installation of baffles, screens or flow deflectors results in an improvement of Sodasorb's effectiveness.

Miller [3] passed various non-reacting gases through Sodasorb and verified that the flow resistance relationship developed by Ward is an appropriate model for flow through Sodasorb.

The objectives of this investigation were:

1. Determine the effect that axial spacers or annular rings installed at various intervals in the Sodasorb bed have on effectiveness by minimizing suspected channelling along the canister walls.
2. Determine the degree of repeatability of the experimental results by repeating similar test runs and comparing those results with both the results of this investigation and with similar runs documented in reference [3].

3. Determine the effectiveness of a previously expended canister by allowing the Sodasorb to regenerate over a specified period of time, and then re-test it.
4. Compare the air flow resistance for a reactant gas with the calculated flow resistance using the relationship derived in reference [3] for a non-reactant gas.

II. SUMMARY OF THEORY

A. CARBON DIOXIDE REMOVAL

Sodasorb is composed of approximately 95% calcium hydroxide with the remainder of the material composed mostly of sodium hydroxide and potassium hydroxide [2]. The material mainly responsible for the carbon dioxide absorption is calcium hydroxide. Carbon dioxide absorption from a gas passing through Sodasorb occurs through chemical neutralization which references [2,5] express as follows:

(i) $CO_2 + H_2O \rightleftharpoons H_2CO_3$

(ii) $(4H^+ + 2CO_3^{=}) + (2Na^+ + 2OH^-) + (2K^+ + 2OH^-) \longrightarrow (2Na^+ + CO_3^{=}) + (2K^+ + CO_3^{=}) + 4H_2O$

(iii) $Ca(OH)_2 + H_2O \longrightarrow (Ca^{++} + 2OH^-) + H_2O$

(iv) $(2Ca^{++} + 4OH^-) + (2Na^+ + CO_3^{=}) + (2K^+ + CO_3^{=}) \rightleftharpoons 2CaCO_3 + (2Na^+ + 2OH^-) + (2K^+ + 2OH^-)$

It is important to understand the significance of the above chemical reactions. How fast the chemical reaction occurs is dependent on the rate H_2CO_3 is removed by the hydroxyl ion reaction shown in equation (ii). The reaction between the H^+ and OH^- ions occurs instantaneously and rapidly exhausts the available OH^- ions. To maintain the carbon dioxide absorption process, hydroxyl ions must be manufactured by the processes

defined in equations (iii) and (iv). It is apparent that the rate of the absorption process is limited by the last two equations and that carbon dioxide removal is directly related to the number of hydroxyl ions present. A slow rate of reaction results in a quicker breakthrough[2] of the canister by the carbon dioxide [2].

Moisture plays an important role in the reaction because the dissolved hydroxides shown in equations (iii) and (iv) are brought into contact with the carbonic acid via the media of a thin liquid film surrounding the Sodasorb particles [2]. Too little water results in an insufficient amount of the hydroxyl ions for the process to proceed at the desired rate; i.e., the reaction rate is too slow. Too much moisture will also result in a slower reaction rate, but not as slow as the rate due to too little moisture. The optimal hydration for Sodasorb has been determined to be in the range from 14 to 19 percent [2]. Moisture is also introduced into the process by that which is contained in a diver's exhaled breath.

The chemical process is an exothermic reaction. Lower ambient temperatures external to the canister will result in a steeper temperature gradient and a proportionally greater dissipation of the canister's heat of reaction. Due to this

[2]Breakthrough is defined as that point in time when the first traces of carbon dioxide are detected in the canister's exhaust.

exothermic reaction, a considerable amount of interest has been generated concerning the effects temperature and moisture have on the reaction process.

Brown [6] questioned if the effectiveness of soda lime was due to the drying out of the particles or to the expiration of the chemical compounds necessary to sustain the reaction. No definitive answer has been found and it appears that both possibilities are feasible. At higher inlet gas temperatures, the carbon dioxide absorption rate will probably be controlled by the amount of moisture retained in the material. At lower air inlet temperatures and as long as hydroxyl ions are produced, the reaction will be rate-controlled by the longevity of the appropriate chemicals shown earlier.

Kinsel [3] presented data supporting his conclusion that dry air entering Sodasorb strips moisture from the absorbent and decreases its effectiveness by approximately 10 - 15% for each $10^{o}F$ drop in temperature between the range of $75^{o}F$ and $0^{o}F$. Obviously in order to make this statement, the volume of Sodasorb used in Kinsel's work had to remain constant. What is not clear is whether the geometrical configuration was also a constant. The effectiveness of Sodasorb can be as much a factor of mass as its canister's geometrical configuration.

Miller's [3] experiments were conducted in the temperature ranges mentioned by Kinsel. It was Miller's conclusion that incoming air temperature is instrumental in Sodasorb's capability to absorb carbon dioxide. This is understandable when it is realized that the absorption process is an exothermic one. Cooler canister environmental temperatures will result in a greater dissipation of the Sodasorb's heat of reaction which means a slower rate of reaction.

Addiani and Byrd [7] experimentally discovered that at inlet air temperatures greater than 28°C (82.4°F) soda lime's effectiveness was for all practical purposes the same.

References [3, 5, 6, 7 and 8] document soda lime's effectiveness as inversely related to the flow rate, percent volume carbon dioxide input, and the quantity of soda lime present.

Conroy and Seevers [8] tested circular cylinders. They experimentally discovered that there existed a "blind spot" of unexpended soda lime. This "blind spot" was located on the centerline, its diameter was approximately one-half the diameter of the cylinder, and it was half the length of the cylinder. Research attributes this "blind spot" to the preferential flow along the cylinder's wall due to channelling. Elam [4 and 9] believes channelling occurs at the interface between the soda lime and the cylinder's wall because at this point the particles are unable to interlock in a uniform manner.

Reference [10] states that a solution to prevent channelling is the installation of annular rings at the entrance, center, and exit of the cylinders in order to direct the flow away from the wall and into the central section. This same reference points out that investigation revealed channelling of air along preferential paths could be enhanced in soda lime by excessive powder called "fines" induced with time by the tendency for a percentage of the granules to pulverize during shipping and handling. To minimize the impact of dusting, the manufacturer has developed a patented anti-dusting film [2].

Elam [4] conducted investigations of flow resistance through soda lime. Miller [3] converted Elam's constant from metric to English units and expressed Elam's relationship as:

$$P = \frac{B\ L\ Q}{A_c} \qquad (1)$$

where L = the Sodasorb bed length

A_c = the cross sectional area of the container

Q = volumetric flow rate

P = the flow resistance

$$B \simeq \frac{.0366 \text{ inches of water - minute}}{ft^2} \qquad \text{(Elam's constant)}$$

One of Miller's objectives was to determine the flow resistance through Sodasorb for three non-reactant gases: nitrogen,

humid air, and air. He compared his results with flow resistant relationships developed by Darcy, Beavers and Sparrow, and Ward. At the completion of his investigation, Miller concluded that the flow resistance model developed by Ward [12] fit his data the best.

Using Ward's flow resistance relationship, pressure drop as a function of Sodasorb's bed length can be expressed as:

$$-\frac{dP}{dx} = \frac{f\rho V_c^2}{k} \tag{2}$$

where $$f = \frac{1}{Re} + .55 \tag{3}$$

$$Re = \frac{\rho V_c \sqrt{k}}{\mu} \tag{4}$$

$$V_c = \frac{Q}{A_c}$$

Q = volumetric flow rate

A_c = cross sectional area of the media container

$\sqrt{k}$ = .004 inches (see reference [3])

Kinsel [5] lists a table of Sodasorb's effectiveness as a function of different batch lots. The mean of the effectiveness is 5.55 ± 0.35 hours, indicating a variation of ± 6.3%.

B. REGENERATION

It has been known for some time by anesthetists that after the initial exhaustion of the absorptive capability of soda lime, and following a sufficient rest without exposure to carbon dioxide, soda lime is re-usable [7, 9 and 11]. Anesthetists believe that this regeneration is due to the greater activity of sodium carbonate to interact with the excess calcium hydroxide and form sodium hydroxide on the particles' surfaces in the following manner:

$$Na_2CO_3 + Ca(OH)_2 \rightleftharpoons 2NaOH + CaCO_3$$

This process is called causticization. It is the formation of a relative strong base from the reaction of a weak acid with a weak base.

Once sodium hydroxide has been reformed, a source of hydroxl ions is available to allow the chemical absorption process to resume once carbon dioxide is again introduced.

Foregger [11] experimentally proved that causticization was in fact the explanation for the regeneration of soda lime.

III. EXPERIMENTAL APPARATUS

The test installation utilized was basically the same as that constructed by Miller [3]. The installation measures the gas flow through the canisters, the volume percentage of carbon dioxide into and out of the canisters, the temperatures and pressures inside the canisters while controlling humidity, the temperature of the incoming gas supply, and the canister environmental temperature. The overall system schematic is shown in Figure 1. The following system description is divided into five subsystems: gas supply and flow measurement, temperature measurement and control, description of the canister, and pressure measurements within the canister.

A. GAS SUPPLY AND FLOW MEASUREMENT

An Ingersol-Rand three-stage, low-pressure, 40-horsepower air compressor was utilized to charge two air banks to 190 psig. The air was filtered and cooled prior to storage in the air bands. A Fairchild Hiller Model 10 air regulator reduced the air pressure to ten psig. The flow rate of air was then controlled by a 3/8-inch gate valve and filtered through a ten micron filter.

The medical grade carbon dioxide was supplied in high pressure cylinders reduced to ten psig by a Matheson Model 8-320 regulator. The carbon dioxide was piped to a Hoke

control valve and then admitted to the main air supply line. The mixture of carbon dioxide and air passed through a half-inch Fischer and Porter Model 10A3500 convertible indicating flowrator meter (shown in Figure 2), rated at 4.6 standard cubic feet per minute at a standard temperature of 70°F and standard pressure of 14.7 psia [13]. The main gas supply line then contained a thermocouple, pressure tap for measuring line pressure, a branch line consisting of a one-half-inch gate bypass-valve and a carbon dioxide measuring probe, and a one-half-inch gate main gas supply-valve. The line pressure was measured using a Meriam type W, 0 - 30 inches of mercury manometer. The gas was then piped to the water bath.

At the water bath, the gas was brought to 100% relative humidity by piping it into the first stage copper-cooling coil, first-stage humidifier, second-stage cooling coil, second-stage humidifier, primary water separator (shown in Figures 1, 3 and 4) and then to the canister.

Prior to entering the canister, the gas passed by a gas sampling probe leading to the infrared detector via a distribution manifold. The infrared detector monitored the volume-percentage of carbon dioxide prior to and at the completion of each run. For the runs of long duration (those in excess of 30 minutes) this probe was periodically employed to verify that the volume-percentage of inlet carbon dioxide to the canister remained constant.

B. CARBON DIOXIDE MEASUREMENT

The gas passed through the canister which was submerged horizontally in the water bath. Upon exiting the Sodasorb, the hot discharge gas entered at the mid-point a 14-inch vertical plexiglas Discharge Chamber bolted to the canister. Some initial condensation occurred in this chamber. Located at the top of the Discharge Chamber were two ports: one port was for the main discharge of gas, while the other port was for the piping of the gas to the infrared detector for sampling. The gas exiting through the main discharge port passed through a 1-inch inside-diameter tube to the atmosphere via a one-half-inch gate-exhaust valve. This exhaust valve maintained the minimum pressure necessary to ensure adequate flow of some of the gas via the sampling port to a modified Wilkes Miran IA (shown in Figure 5) variable filter infrared analyzer. The gas exiting the Discharge Chamber via the sampling port passed through a one-fourth-inch inside-diameter tube to a distribution manifold via a condenser. From the manifold, the sampling gas was dehumidified by passing through a vertical bed of anhydrous indicating Drierite ($CaSO_4$). (See Figure 5) The incoming gas to the infrared detector was at atmospheric temperature.

The infrared detector was calibrated prior to and upon completion of each run with nitrogen, 0.5%, 1.0%, 4.0%, 6.0%

and 8.0% by volume carbon dioxide and premixed nitrogen. These calibration gases were available through a distribution manifold with air quick-disconnects.

Prior to each run, the canister input gas was sampled from the rotameter exhaust tap port. After termination of each run, the input gas was sampled from both the rotameter exhaust and the canister input port. These samples were compared to the desired calibration nitrogen and carbon dioxide premixed gases. The infrared detector was utilized in an open loop mode at a wavelength of 4.25 micrometers, slit of 2 millimeters, gain of 10, and the continuous gain was fine-tuned to a meter reading of zero with nitrogen purging the test cell. The time constant on the infrared detector was one second. The scale was set at one times absorption, and the pathlength was set at 40 meters.

C. TEMPERATURE MEASUREMENT AND CONTROL

The bath temperature was controlled by cooling and stabilizing the bath temperature with a constant-temperature circulating water bath constructed at the Naval Postgraduate School. The controller utilized to maintain the desired temperature was a Versa Therm Proportional Electronic Temperature Controller, Model 2156. The controller settings for the various bath temperatures are shown in Table I. A photograph of the water bath and the Temperature Controller are shown in Figures 6 and 7.

Temperatures were monitored in the canister, at the exhaust of the flowmeter, and in the water bath with Omega stainless-steel-sheathed exposed-junction copper-constant thermocouples. (See Figures 8 and 9) The thermocouples outputs were directed through a 24-element switch to a Newport Model 267 digital pyrometer that indicated temperature in degrees Fahrenheit. The thermocouples in the canisters measured temperatures at the zero, one-inch and two-inch radius as measured from the center. The distances between the thermocouples varied for the canisters. The distances are listed in Appendix A and are schematically depicted in Figures 8 and 9.

D. DESCRIPTION OF THE CANISTERS

Two canisters were used in this investigation to evaluate Sodasorb's effectiveness. Both canisters had an inside-diameter of four-inches and could have their length-to-diameter ratios varied from 1.225 to 2.125. The Sodasorb was contained at the gas inlet and exhaust by fine wire-mesh screens composed of 0.17 inches diameter wire of 18 squares per linear inch. The openings between the wires were .00149 square inches and 48% of the screen's total cross-sectional area was void [3].

All tests with axial spacers were conducted using a canister constructed from one-half-inch wall thickness plexiglas tubing of length twelve inches. (See Figures 8, 9 and 10) All of the initial and repeat test runs were also made using this

canister. Tail-piece spacers were utilized to vary the length of the canister's bed. The length-to-diameter ratios tested were 1.225, 1.60 and 2.125. Stainless-steel spacers with square mesh screens were used in the canister to obtain one-half-inch axial spaces at various intervals in the Sodasorb bed. Tests were conducted with either one spacer located at the midpoint of the bed ($x/L = 0.5$) or two spacers located at one-third intervals in the bed ($x/L = 0.333$ and $x/L = 0.667$), where "x" is the distance measure from the incoming gas screen along the length of the canister. The screens used with the axial spacers were the same mesh as the screens located at the inlet and exhaust ends of the Sodasorb bed.

Test employing annular rings were conducted using a canister constructed in sections from 3/8-inch wall thickness acrylic plexiglas tubing. (See Figure 11) Entrance and tail-piece spacers, and mid-body canister sections of the appropriate length, were utilized to set the length-to-diameter ratio of the bed at either 1.225, 1.60 or 2.125. Figure 11 schematically illustrates the locations of both the spacers and the general assembly of the canisters with the mid-body sections. The number of annular rings could be varied from zero to four. The inside diameter of the rings was 3.5 inches. The screens utilized in this canister were of the same mesh as the screens described in the previous canister.

The second canister was designed to ensure no gas flow between the canister's wall and the annular rings. It was also desired that a tight pack of Sodasorb on either side of the annular rings be obtained. To accomplish these goals, it was necessary to sectionalize the canister. A disadvantage of this design was that construction did not allow the same number of pressure and temperature probes as the first canister. Specifically, pressure and temperature probes could not be located in an area downstream from the gas exhausting from the Sodasorb bed. Also, the longitudinal position of the probes was not the same for both canisters. (See Appendix A)

E. PRESSURE MEASUREMENTS WITHIN THE CANISTER

The axial pressure difference across the Sodasorb bed was monitored in the canisters for given length-to-diameter ratios at the points specified in Appendix A. Pressure-tap holes along the canister's length were 1/16-inch diameter and connected to a manifold for selecting the desired pressure position. Pressures were indicated on either an Ellision four-inch, two-inch or half-inch inclined manometer.

F. REGENERATIVE RUNS

The initial run was made in accordance with the experimental procedures outline in Appendix B, sections A through G. Upon completion of the run, the infrared detector was immediately

purged with nitrogen. The input percentage of carbon dioxide was measured and recorded. The gas supply valve to the canister at the rotameter exhaust was closed and the bypass valve opened. The bypass pressure as indicated on the 30-inch mercury manometer was recorded. The canister was then allowed to remain in the water bath for forty-five minutes without any air flow. At the completion of the forty-five minutes, the Hoke Control valve in the main air supply line was adjusted to ensure the bypass pressure was the same as it was at the time of the initial securing. At the appropriate time the supply valve to the canister was opened and the bypass valve shut. The run then continued through to completion in accordance with the procedures outline in Appendix B, sections G and H.

IV. PRESENTATION OF RESULTS

A total of 108 test runs were conducted. Seventeen tests were invalidated due to procedural errors or improperly assembled canisters. Twenty-seven tests were made in an attempt to duplicate the results for similar tests reported in reference [3]. Forty-one tests were made with axial spacers, each spacer one-half inch in length. Nine tests were made to verify repeatability and twelve tests were made with annular rings. Two tests were made to evaluate the regenerative characteristics of Sodasorb.

All input volumetric flow rates contained 6.0% by volume carbon dioxide. Canister inlet gas and environmental temperatures were directly determined by the water bath temperature. The volumetric flow rate of the gas was determined in accordance with the procedures contained in Appendix D.

Tables II through VI show the experimental data recorded for the tests evaluating Sodasorb effectiveness by itself and with either axial spacers or annular rings. Tables III and IV show incomplete readings for the tests scheduled at a water bath temperature of 40°F. These tests were not made due to time constraints. No trend of improvement in effectiveness using axial spacers had been noted at the higher bath temperatures nor indicated in the few tests conducted at 40°F. In the interest of completing all objectives the remaining tests with axial spacers at 40°F were cancelled.

Figures 13, 14 and 15 plot Sodasorb's effectiveness as a function of volumetric flow rate. The canister length-to-diameter ratios were 2.125, 1.60 and 1.225 respectively. The test results for water bath temperatures of $70^{o}F$, $55^{o}F$ and $40^{o}F$ are shown.

Sodasorb's effectiveness dependence on canister length-to-diameter ratio for varying volumetric flow rates at constant water bath temperatures is shown in Figures 16, 17 and 18. Sodasorb's effectiveness for similar volumetric flow rates as a function of varying length-to-diameter ratios and water bath temperatures is shown in Figures 19, 20 and 21.

This investigation conducted tests varying the Sodasorb mass with its geometrical configuration. For similar volumetric flow rates and water bath temperatures, the data from Table II was to used to calculate effectiveness as a function of mass. This data is presented in Table VIII and graphically depicted in Figures 22 through 27. Sample calculations used to make Table VIII are shown in Appendix F.

Figures 28 through 34 are comparisons of the same length-to-diameter canister ratios both with and without axial spacers. For a given canister ratio and water bath temperature, each figure shows Sodasorb's effectiveness as a function of volumetric flow rate.

Sodasorb's effectiveness as a function of volumetric flow rate with spacers, without spacers and with annular rings is

shown in Figures 35, 36 and 37. The results are plotted for constant canister length-to-diameter ratios of 2.125, 1.60 and 1.225, and a water bath temperature of 70°F.

Figures 38 through 43 are comparisons of the results of this investigation with those tabulated for similar tests in reference [3].

Figures 44 through 49 are plots of canister radial temperatures as a function of the elapsed run time at Station 3, x/L = .382, and Station 4, x/L = .559. The length-to-diameter ratio was 2.125 and the water bath temperature was 70°F. The six figures are for three volumetric flow rates: two each at 1.06, 2.10 and 2.90 SCFM.

Plots showing radial temperatures for canisters with annular rings as a function of elapsed run time with set length-to-diameter ratio of 2.125 and at a water bath temperature of 70°F are shown in Figures 50 through 53.

Plots comparing the radial temperatures of similar length-to-diameter canister ratios at the three radii as well as at Stations 3, x/L = .50, or Station 4, x/L = .810, are shown in Figures 54 through 59.

Figures 60 through 65 are comparisons of radial temperatures for the regenerative tests. The canister length-to-diameter ratio was 2.125 and the volumetric flow rate was 2.08 SCFM. The water bath temperature was 70°F. Each

figure plots radial temperature as a function of elapsed run time for one of three radii at one of the two stations (either Station 3, x/L = .50, or Station 4, x/L = .810).

Figures 66, 67 and 68 depict Sodasorb bed temperatures at specific times in the test. No spacers or rings were present. Figures 69, 70 and 71 also show the bed temperatures at specific times, but these figures represent tests in which annular rings were present. For all six figures the length-to-diameter ratio was 2.125 and the water bath temperature was 70°F. Each figure is for one of the volumetric flow rates of either 1, 2 or 3 SCFM.

Table VII presents the results obtained in the regenerative tests.

Table IX and Figures 72, 73 and 74 compare the actual pressure drop across a bed of Sodasorb with the values predicted by Elam, Ward and the author. Elam's and Ward's flow resistance relationships were based on flow of a non-reactant gas through a porous media. The author's flow resistance relationship was derived by applying Ward's relationship to the data gathered during this investigation.

The pressure probe at the entrance to the Sodasorb bed was positioned just forward of the screen. Sodasorb by volume occupies approximately 47% of the canister's volume [3]. Although a pressure drop due to a sudden contraction occurs

at the entrance to the canister, application of Bernoulli's equation substantiates that the pressure drop is negligible.

The canister was always tested with the Sodasorb bed in the horizontal position. For the sudden contraction of the gas at the screen entrance, Bernoulli's equation can be simplified as follows:

$$\frac{\rho V_{c1}^2}{2} + P_1 = \frac{\rho V_{c2}^2}{2} + P_2$$

where P_1 and V_{c1} are conditions upstream of the screen and P_2 and V_{c2} are the conditions downstream.

Equation (1) can be expressed as:

$$P_1 - P_2 = \frac{1}{2} (V_{c2}^2 - V_{c1}^2)$$

For Q = 3.0 SCFM and $A_{c2} = .47\ A_{c1}$,

$$V_{c1} = \frac{Q}{A_{c1}} = .573 \frac{ft}{sec}$$

$$V_{c2} = \frac{Q}{A_{c2}} = 1.219 \frac{ft}{sec}$$

For this investigation,

$$P_1 \simeq 15.45 \frac{lb_f}{in^2} \qquad \rho \simeq .075 \frac{lb_m}{ft^3}$$

so that

$$P_1 - P_2 = 9.37 \times 10^{-6} \frac{lb_f}{in^2} = 2.6 \times 10^{-4}\ " H_2O$$

The Sodasorb batch lots, date of manufacture and inclusive dates of testing are shown below:

Sodasorb Batch Lot	Date of Manufacture	Date of Testing
AG02-4004-7	February 7, 1977	17 May - 27 May
AK07-4004-16	July 16, 1979	11 May - 16 May
AL03-4004-26	March 26, 1980	28 May - 20 June
AL06-4004-5	June 5, 1980	7 July - 16 July

The repetitive tests were made using Sodasorb from batch lot AL03-4004-26 and compared with the results using Sodasorb from batch lot AG02-4004-7. At the time of the initial tests, the Sodasorb used was 10 months old; the Sodasorb used in the repeat tests was 3 months old.

V. DISCUSSION OF RESULTS

For volumetric flow rates of approximately 1 and 2 SCFM, Figures 13, 14 and 15 in general support Kinsel's [5] conclusion that there is a 10 - 15% decrease in effectiveness for each $10^{o}F$ drop in the canister's environmental temperature between $75^{o}F$ and $0^{o}F$. However, at volumetric flow rates of 3 SCFM and length-to-diameter ratios of 1.225 and 1.60 these same figures show that the canister's environmental temperature has little impact on effectiveness.

For the canister geometries and volumetric flow rates tested, Figures 16, 17 and 18 show that Sodasorb's effectiveness is degraded more by the decrease in geometrical ratio than by the incoming gas and canister environmental temperatures. This degradation is shown by both Figures 19, 20 and 21, and Figures 22, 23 and 24 to be nearly a linear function of the length-to-diameter ratio.

Figures 22 through 27 are plots for either similar volumetric flow rates or environmental temperatures of Sodasorb's effectiveness as a function of mass. As a function of mass these figures show that Sodasorb's environmental temperature does not have a significant influence on effectiveness.

At volumetric flow rates of 2 and 3 SCFM Figures 28, 29 and 30 show Sodasorb's effectiveness for canisters with axial

spacers was in general equal to that of the canisters without spacers. The only improvement was observed at the volumetric flow rate of 1 SCFM shown in Figure 28.

With one exception Figures 35, 36 and 37 show that Sodasorb effectiveness for canisters with annular rings was equal to or slightly better than for canisters without annular rings.

A comparison of the results for similar test runs shown in Figures 44 through 52 reveal that canisters with annular rings have wall temperatures substantially less than the canisters without rings. Actually, the temperatures of the Sodasorb at the wall of the annular ring canisters approaches closely the temperature of the water bath. At Station 3, x/L = .382 (without rings) and .50 (with rings), the cross-sectional temperature profiles of the annular ring canisters appear to have a more uniform radial temperature gradient than the canisters without rings. At Station 4, x/L = .559 (without rings) and .810 (with rings), the radial temperature gradients for both canisters are similar.

The results of the repeatability tests are shown in Figures 38, 39 and 40. These variations in repeatability are probably due to the varying moisture entrapped in the Sodasorb and in the increasing powdering of the granulars with age due to shipping and handling. In all cases, the higher effectiveness shown were obtained using a newer Sodasorb batch lot.

Correlation of test runs conducted during this investigation with similar tests documented in reference [3] are shown in Figures 41, 42 and 43. Correlation at the higher volumetric flow rates was generally good but considerable scatter existed at the lower volumetric flow rates.

Table VI shows that for a length-to-diameter canister ratio of 2.125, canister environmental temperature of 70°F, and a volumetric flow rate of 2 SCFM, and following the initial expiration of the canister with a 45 minute rest period free of the presence of carbon dioxide, regeneration occurred and the canister could be used again with an effective life span of approximately 19% (± 0.5%) the canister's initial life span. Figures 50 through 55 show that for the regenerated test runs, the heat of reaction was considerably less uniform than for the initial runs.

Experimentally observed pressure drops across the Sodasorb bed for three volumetric flow rates of 1, 2 and 3 SCFM are plotted in Figures 72, 73 and 74. Also plotted on the same figures are the predicted pressures drops for similar conditions using the relationships developed by Elam and Ward as shown in Section II of this report. Upon reviewing these figures, it was noted that if Ward's flow resistance constant was changed from 0.55 to 1.67, the resultant theoretical pressure drops across the Sodasorb bed compared favorably with the experimental

data. A plot of predicted pressure drops across the bed using 1.67 as the constant in Ward's relationship is also shown on these figures. Sample calculations used in determining the theoretical pressure drop are shown in Appendix G.

VI. CONCLUSIONS

Based upon the results of this investigation the following conclusions are made:

1. The installation of either axial spacers or annular rings in the Sodasorb bed did not result in any significant improvement in effectiveness. For the canister configurations and volumetric flow rates evaluated in this investigation, channelling does not appear to be a significant factor.
2. The repeatability of results within the tolerances published by the manufacturer could not always be duplicated. The wide variations in repeatability is ascribed to varying moisture content in Sodasorb and to a gradual breakdown with time of the material's granular structure due to shipping and handling resulting in variable effectiveness.
3. For volumetric flow rates of approximately 2 SCFM, canister length-to-diameter ratio of 2.125, and water bath temperature of 70°F, the effectiveness of the regenerated Sodasorb was experimentally determined to be 19% that of the unused Sodasorb.
4. For the geometrical configurations, environmental conditions and volumetric flow rates of this investigation, the Fanning friction factor for 6% by

volume carbon dioxide flow through Sodasorb is best represented by the following relationship:

$$f = \frac{1}{Re} + 1.67$$

VII. RECOMMENDATIONS FOR FURTHER STUDY

Based on the results of the experimental data obtained in this investigation the following recommendations for further investigation are submitted:

1. In further investigations on the impact canister configurations have on effectiveness, it is recommended that a constant mass of 3 lbs of Sodasorb be used. Two such investigations have resulted in a considerable amount of data being accumulated for 3.0 lbs of Sodasorb. A mass of 3.0 lbs corresponds to the four-inch inside-diameter canister with a length-to-diameter ratio of 2.125 used in reference [3] and this investigation.
2. The absorption process rate of reaction is influenced by temperature. A better knowledge of Sodasorb's heat generation rate and its impact on effectiveness is necessary. Real-time continuous recording of inside canister temperatures during tests should therefore be made.
3. Assuming heat generation does impact significantly on the absorption process, investigation of Sodasorb's effectiveness for small length-to-diameter canister configurations should be made. A smaller length-to-diameter ratio canister may result in a more uniform

cross-sectional temperature gradient. If it does, it is expected that for the same mass of Sodasorb, the smaller length-to-diameter canister will prove more effective.

TABLE I

CONSTANT TEMPERATURE WATER BATH REFRIGERATION UNIT

1. Settings:

Desired Bath Temperature	Expansion Valve	Temperature Controller Voltage	Coarse	Fine	Range
40°F	20	7	0	0	1
55°F	20	7	8	0	1
70°F	20	7.5	14	14	1

2. Liquid: Distilled or deionized water

3. Refrigeration Timer: As set, with the maximum run time at approximately 80%.

4. Water Bath Circulation: Circulation by water pump kept dry and primed. To maximize temperature control, take suction from the water bath and discharge at the surface of the refrigeration.

5. Water Bath Level: Controlled by the use of two large syphon lines.

6. Comments: Temperature established when both A and B lights are lit with equal intensity. Refer to instruction for Proportional Electronic Temperature Controller, Model No. 2156 and Proportional Power Multiplier Model No. 2156-1, for additional information on utilization of the controller. Use Freon 502 only.

TABLE II

SODASORB EFFECTIVENESS FOR VARIABLE L/D CANISTER WITH NO AXIAL SPACERS

Test Run #	L/D	T (^{o}F)	$\dot{Q}_s$ (SCFM)	$t_{1/2}$ (min)
1	2.125	70	1.06	81
2	2.125	70	2.07	37
3	2.125	70	2.90	22.5
9	1.60	70	1.19	54
8	1.60	70	1.97	21.5
7	1.60	70	2.86	10
15	1.225	70	1.03	47.5
14	1.225	70	2.04	12
13	1.225	70	2.97	3.5
30	2.125	55	1.07	83.5
29	2.125	55	2.10	32.5
28	2.125	55	3.19	19
36	1.60	55	1.02	53.5
35	1.60	55	1.97	20.5
34	1.60	55	3.08	8
42	1.225	55	1.08	36
41	1.225	55	2.21	11
40	1.225	55	3.13	5
57	2.215	40	1.13	73
56	2.125	40	2.01	29
55	2.125	40	3.06	9
63	1.60	40	1.10	53.5
62	1.60	40	2.07	16.5
61	1.60	40	3.06	5.5
69	1.225	40	1.03	34
68	1.225	40	2.17	6
67	1.225	40	3.04	3

TABLE III

SODASORB EFFECTIVENESS FOR VARIABLE L/D CANISTER WITH ONE AXIAL SPACER

Test Run #	L/D	T (^{o}F)	Q_s (SCFM)	$t_{\frac{1}{2}}$ (min)
6	2.125	70	1.15	83.5
5			2.03	33
4			3.47	12.5
12	1.60	70	1.13	50.5
11			2.04	13.5
10			2.92	6.5
18	1.225	70	1.04	44
17			1.98	12
16			2.91	5
33	2.125	55	1.08	68.5
32			2.07	27.5
31			3.16	16
39	1.60	55	1.08	52
38			2.07	13.5
37			3.07	8
45	1.225	55	1.13	36.0
44			2.11	8.5
43			2.98	5.5
60	2.125	40	1.06	63
59			2.06	23.5
58			3.00	7
66	1.60	40	1.03	41
65				
64				
72	1.225	40		
71				
70				

TABLE IV

SODASORB EFFECTIVENESS FOR VARIABLE L/D CANISTER WITH TWO AXIAL SPACERS

Test Run #	L/D	T (^{o}F)	Q_s (SCFM)	$t_{\frac{1}{2}}$ (min)
21	2.125	70	1.12	93.5
20			2.03	36.5
19			3.13	18.5
24	1.60	70	1.02	60
23			2.17	25.5
22			2.79	8
27	1.225	70	0.98	41.5
26			2.12	6.5
25			2.69	3.5
48	2.125	55	1.03	85.5
47			2.09	30.5
46			3.09	12.5
51	1.60	55	1.03	56.5
50			2.21	14
49			3.01	7
54	1.225	55	1.09	32
53			2.11	10
52			3.00	3.5
75	2.125	40	1.01	70.5
74				
73				
78	1.60	40		
77				
76				
81	1.225	40		
80				
79				

TABLE V

SODASORB EFFECTIVENESS FOR VARIABLE L/D CANISTER WITH ANNULAR RINGS

Test Run #	L/D	T (^{o}F)	Q_s (SCFM)	$t_{\frac{1}{2}}$ (min)
102	2.125	70	1.12	89
103	2.125	70	2.08	40
100	2.125	70	3.12	19
107	1.60	70	1.15	58.5
108	1.60	70	2.11	26.0
109	1.60	70	3.10	12.5
105	1.225	70	1.03	43.5
106	1.225	70	2.07	13.5
104	1.225	70	3.14	6.0

TABLE VI

SODASORB EFFECTIVENESS FOR VARIABLE L/D CANISTER
REPEAT RUNS WITH NO SPACERS

Test Run #	L/D	T (^{o}F)	Q_s (SCFM)	$t_{1/2}$ (min)
R-5	2.125	70	1.05	94
R-1	2.125	70	1.09	92
111	2.125	70	2.08	38.5
110	2.125	70	2.10	40.5
R-2A	2.125	70	3.06	33.5
R-4	2.125	70	3.09	26.5
R-8	1.60	55	1.07	62
R-6	1.60	55	2.02	22.5
R-10	1.60	55	3.15	5.
R-11A	2.125	40	1.05	63.5
R-12	2.125	40	3.09	9.0
R-3	2.125	77	1.07	103.5

TABLE VII

SODASORB EFFECTIVENESS FOR REGENERATIVE RUNS

Test Run #	L/D	T (^{o}F)	Q_s (SCFM)	$t_{\frac{1}{2}}$ (min)
110-Part I	2.125	70	2.10	40.5
110-Part II	2.125	70	2.14	7.5
111-Part I	2.125	70	2.08	38.5
111-Part II	2.125	70	2.08	7.5

TABLE VIII

COMPARISON OF CANISTER EFFECTIVENESS AS A FUNCTION OF SODASORB MASS FOR SIMILAR FLOW RATES

	Test Run #	L/D	T (^{o}F)	Q (SCFM)	t_{112}	$\frac{M_{(\quad)}}{M_{(2.125)}}$	$\frac{t_{1/2(\quad)}}{t_{1/2\,(2.125)}}$
Q~1.0 SCFM	1	2.125	70	1.06	81	1.0	1.0
	9	1.60	70	1.19	54	.753	.667
	15	1.225	70	1.03	47.5	.576	.586
	30	2.125	55	1.07	83.5	1.0	1.0
	36	1.60	55	1.02	53.5	.753	.641
	42	1.225	55	1.08	36	.576	.431
	57	2.125	40	1.13	73	1.0	1.0
	63	1.60	40	1.10	53.5	.753	.733
	69	1.225	40	1.03	34	.576	.465
Q~2.0 SCFM	2	2.125	70	2.07	37	1.0	1.0
	8	1.60	70	1.97	21.5	.753	.581
	14	1.225	70	2.04	12	.576	.324
	29	2.125	55	2.10	32.5	1.0	1.0
	35	1.60	55	1.97	20.5	.753	.631
	41	1.225	55	2.21	11	.576	.338
	56	2.125	40	2.01	29	1.0	1.0
	62	1.60	40	2.07	16.5	.753	.569
	68	1.225	40	2.17	6	.576	.207
Q~3.0 SCFM	3	2.125	70	2.90	22.5	1.0	1.0
	7	1.60	70	2.86	10	.753	.444
	13	1.225	70	2.97	3.5	.576	.155
	28	2.125	55	3.19	19	1.0	1.0
	34	1.60	55	3.08	8	.753	.421
	40	1.225	55	3.13	5	.576	.263
	55	2.125	40	3.06	9	1.0	1.0
	61	1.60	40	3.06	5.5	.753	.611
	67	1.225	40	3.04	3	.576	.333

TABLE IX

AIR FLOW RESISTANCE THROUGH SODASORB AS A FUNCTION OF THE BED'S LENGTH

a) Test Run Number: R-1
Length-to-Diameter Canister Ratio: 2.125
Mean Volumetric Flow Rate: 1.09 SCFM
Water Bath Temperature: 70°F
Effectiveness: 92 min

Distance in inches from entrance to Sodasorb bed	Elapsed Run Time					
	12 min		88.5 min			
	Average Canister Temperature					
	121.1°F		105.5°F		121.°F	
	Instanteous Volumetric Flow Rate					
	1.10 SCFM		1.09 SCFM		1.10 SCFM	
	Pressure Drop (inches H_2O)					
	CO_2[1]	Ward[2]	CO_2[1]	Ward[2]	Elam[3]	Author[3]
1.375		.021		.020	.052	.028
1.75	.02	.026	.02	.026	.066	.035
3.25	.06	.049	.05	.048	.124	.066
4.25		.064		.062	.162	.086
4.75	.10	.071	.08	.069	.181	.096
6.25	.14	.093	.11	.091	.238	.127
6.875		.103		.101	.262	.139
8.50	.17	.127	.14	.124	.324	.172

Notes: (1) The Air Flow Resistance as measured during the experimental test runs.

(2) Reference [3] verified Ward's flow resistance through Sodasorb for Nitrogen (a non-reactant gas). The Flow Resistance Values in this column are calculated from that relationship, using the length of Sodasorb Bed, cross-sectional area of the canister and volumetric flow rate.

(3) Predicted Values based on relationships developed in Sections II and V.

TABLE IX
(continued)

b) Test Run Number: 110
Length-to-Diameter Canister Ratio: 2.125
Mean Volumetric Flow Rate: 2.10 SCFM
Water Bath Temperature: 70°F
Effectiveness: 40 1/2 min

Distance in inches from entrance to Sodasorb bed	Elapsed Run Time					
	8.5 min		31 min		8.5 min	
	Average Canister Temperature					
	115.6°F		106.9°F		115.6°F	
	Instanteous Volumetric Flow Rate					
	2.10 SCFM		2.09 SCFM		2.10 SCFM	
	Pressure Drop (inches H_2O)					
	CO_2[1]	Ward[2]	CO_2[1]	Ward[2]	Elam[3]	Author[3]
1.375	.10	.046	.10	.045	.101	.075
1.75		.058		.058	.128	.096
3.25		.108		.107	.289	.178
4.25	.18	.142	.23	.140	.312	.233
4.75		.158		.157	.349	.261
6.25		.208		.206	.459	.343
6.875	.43	.229	.40	.227	.505	.377
8.50		.283		.280	.624	.466

Notes: (1) The Air Flow Resistance as measured during the experimental test runs.

(2) Reference [3] verified Ward's flow resistance through Sodasorb for Nitrogen (a non-reactant gas). The Flow Resistance Values in this column are calculated from that relationship, using the length of Sodasorb Bed, cross-sectional area of the canister and volumetric flow rate.

(3) Predicted Values based on relationships developed in Sections II and V.

TABLE IX
(continued)

c) Test Run Number: R-4
Length-to-Diameter Canister Ratio: 2.125
Mean Volumetric Flow Rate: 3.09 SCFM
Water Bath Temperature: 70°F
Effectiveness: 26.5 min

Distance in inches from entrance to Sodasorb bed	Elapsed Run Time					
	11.5 min		20 min		20 min	
	Average Canister Temperature					
	108.8°F		116.9°F		108.8°F	
	Instanteous Volumetric Flow Rate					
	3.08 SCFM		3.11 SCFM		3.11 SCFM	
	Pressure Drop (inches H_2O)					
	CO_2 (1)	Ward (2)	CO_2 (1)	Ward (2)	Elam (3)	Author (3)
1.375		.078		.079	.148	.144
1.75	.15	.100	.15	.101	.189	.183
3.25	.30	.185	.30	.188	.351	.340
4.25		.242		.245	.459	.444
4.75	.47	.270	.47	.274	.513	.500
6.25	.65	.356	.64	.361	.675	.653
6.875		.391		.397	.742	.719
8.50	.89	.484	.88	.491	.912	.890

Notes: (1) The Air Flow Resistance as measured during the experimental test runs.

(2) Reference [3] verified Ward's flow resistance through Sodasorb for Nitrogen (a non-reactant gas). The Flow Resistance Values in this column are calculated from that relationship, using the length of Sodasorb Bed, cross-sectional area of the canister and volumetric flow rate.

(3) Predicted Values based on relationships developed in Sections II and V.

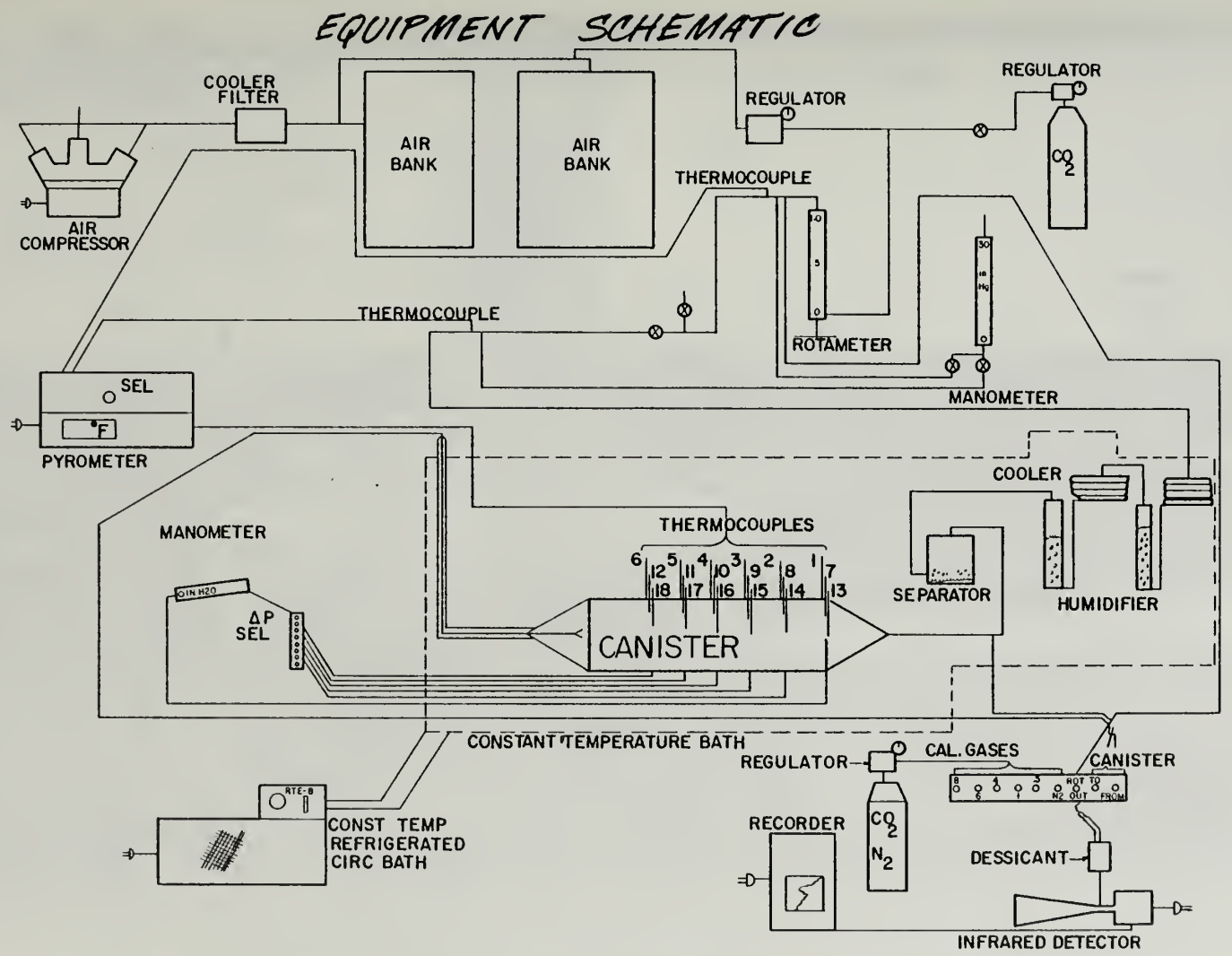


Figure 1. Equipment Schematic

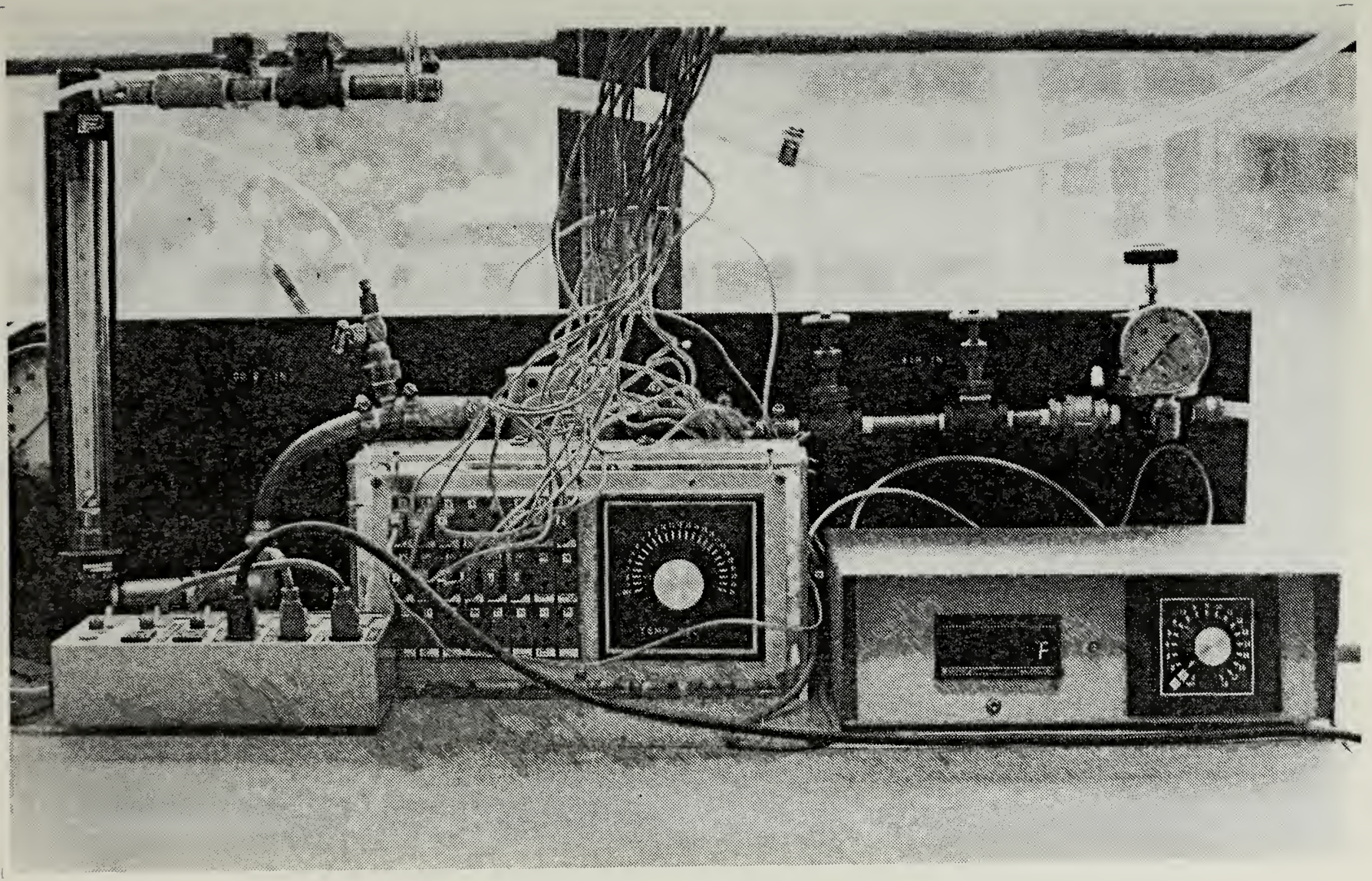


Figure 2. Flowmeter and Temperature Selector.

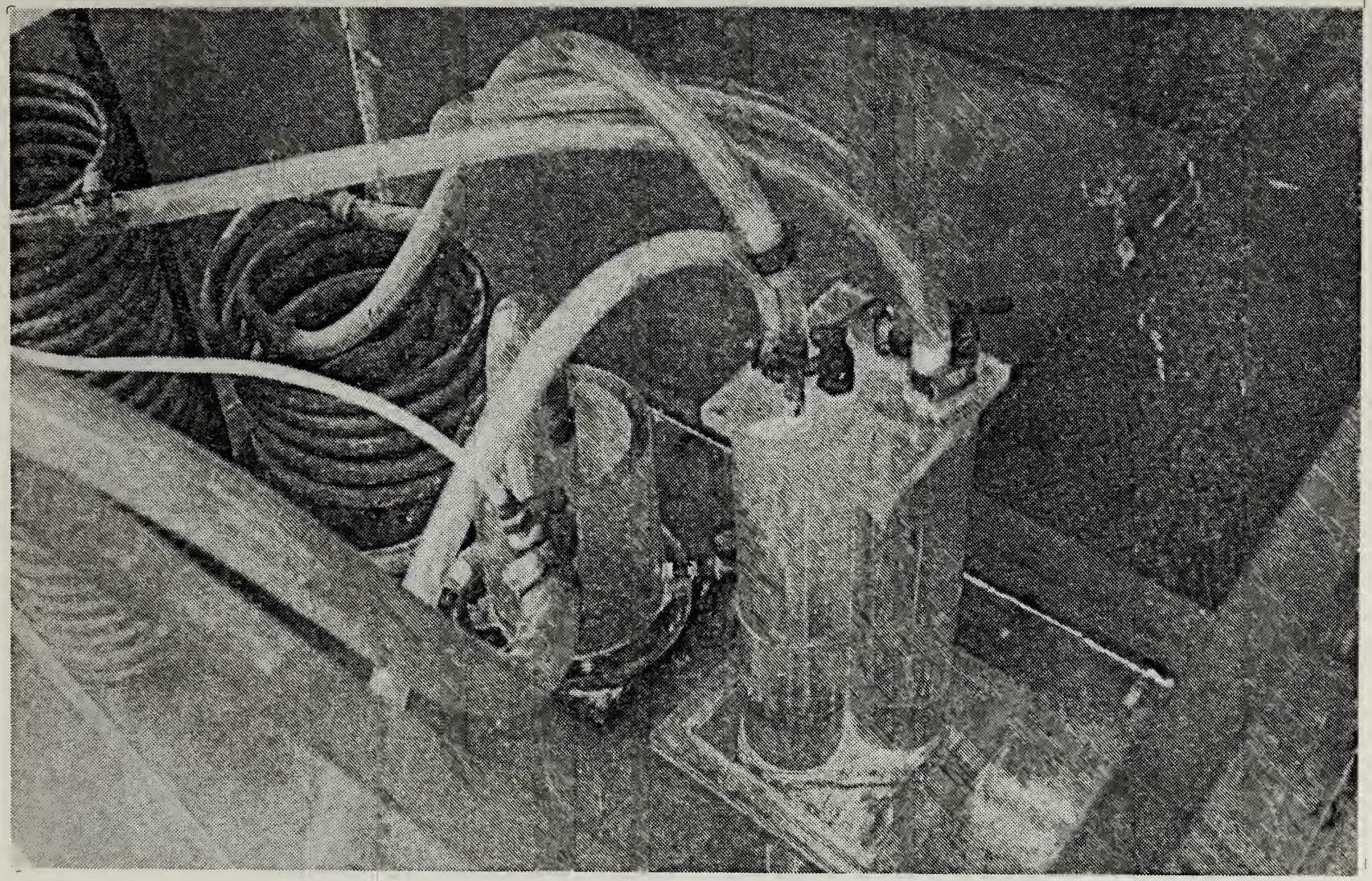


Figure 3. Humidifiers and Primary Water Separator.

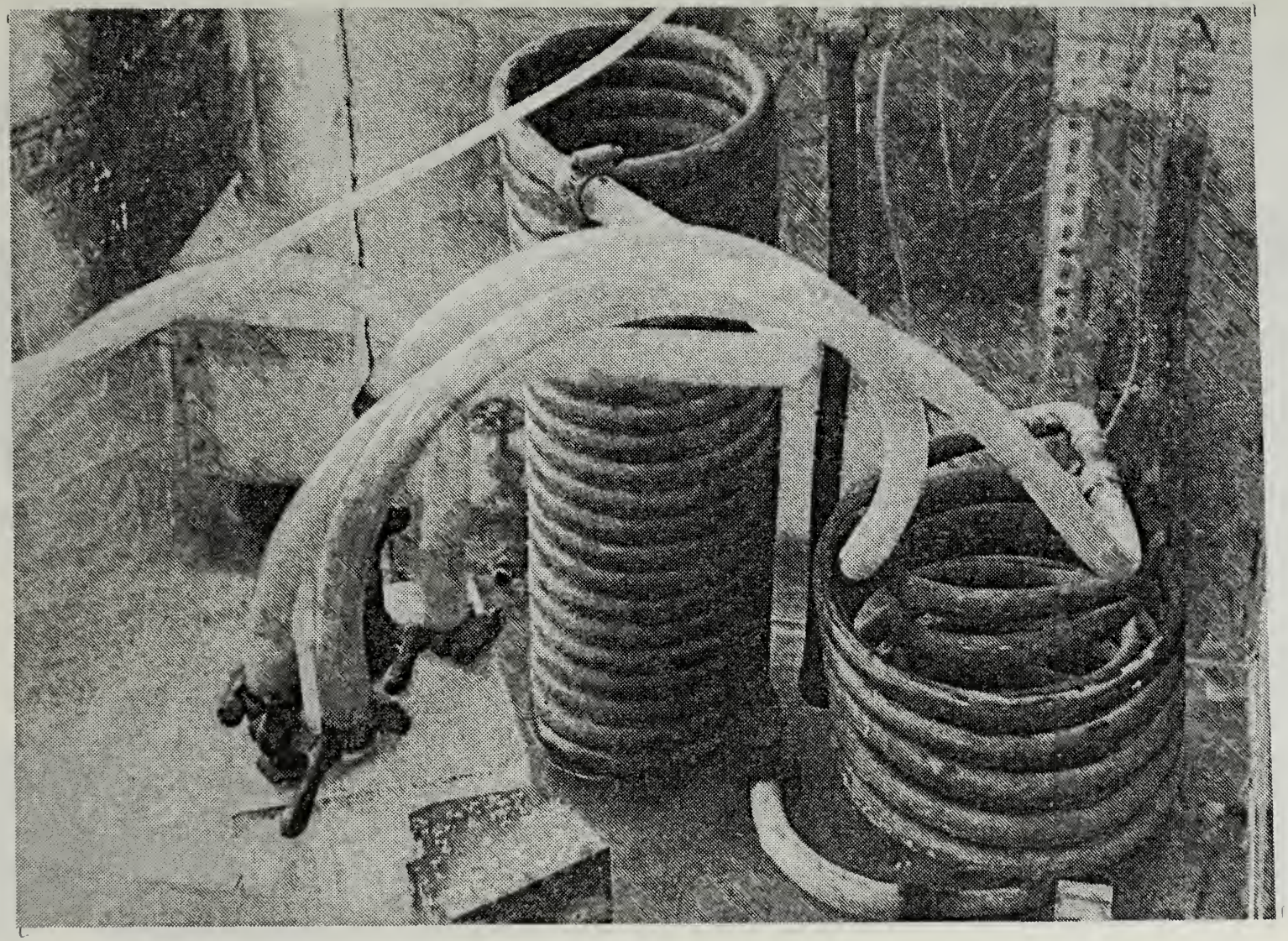


Figure 4. Cooling Coils.

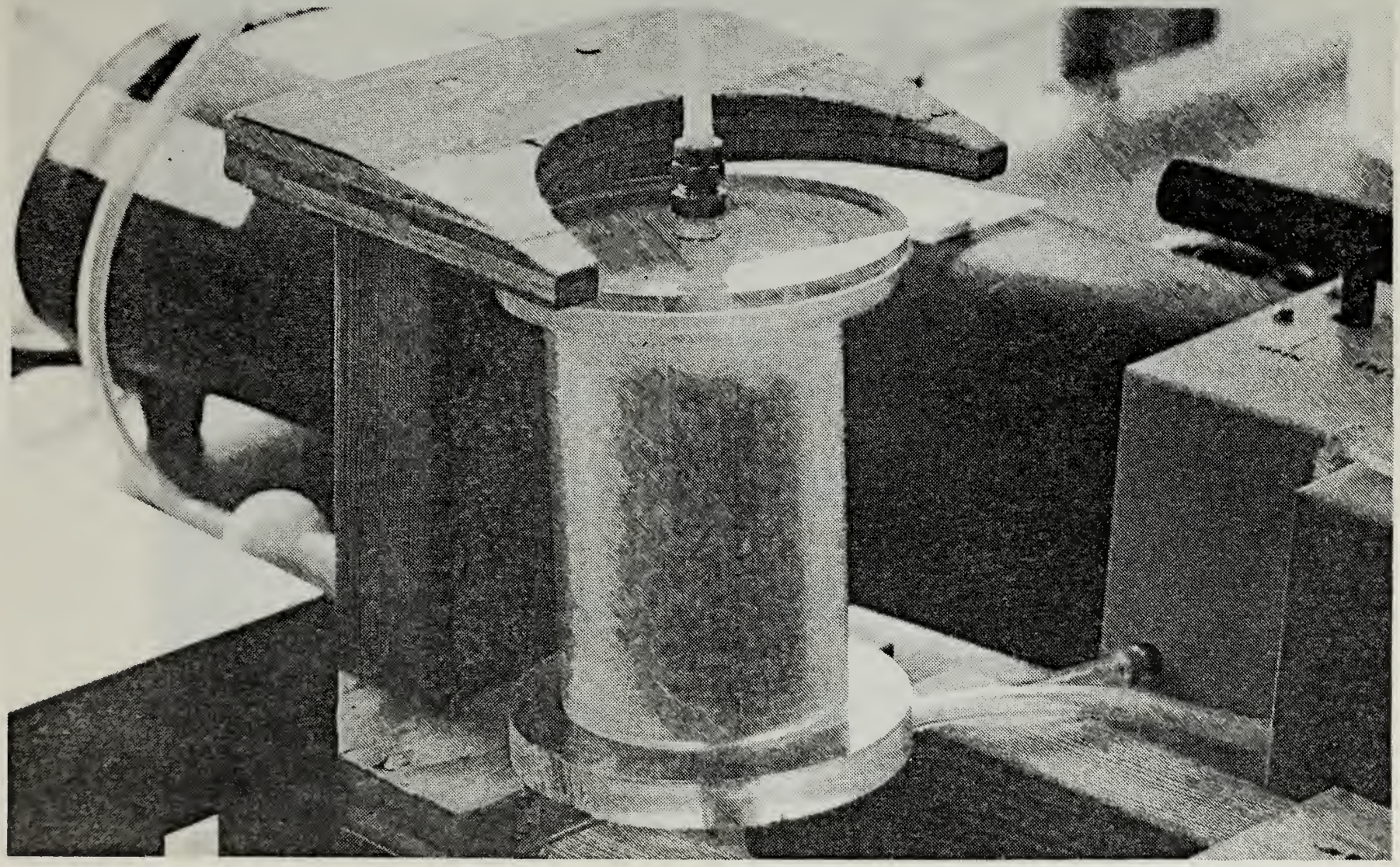


Figure 5. Infrared Detector and Primary Dessicant.

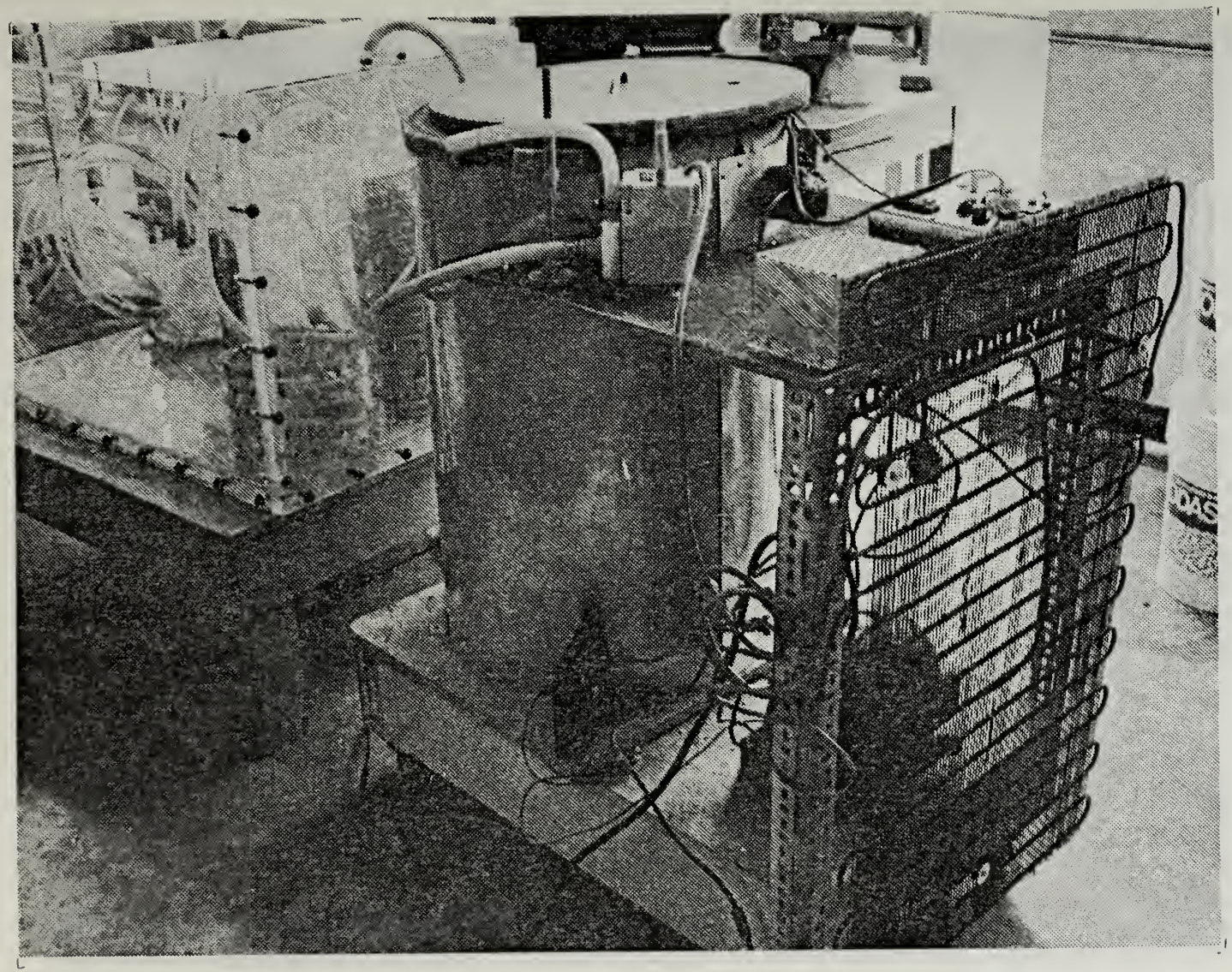


Figure 6. Constant-Temperature Circulating Water Bath

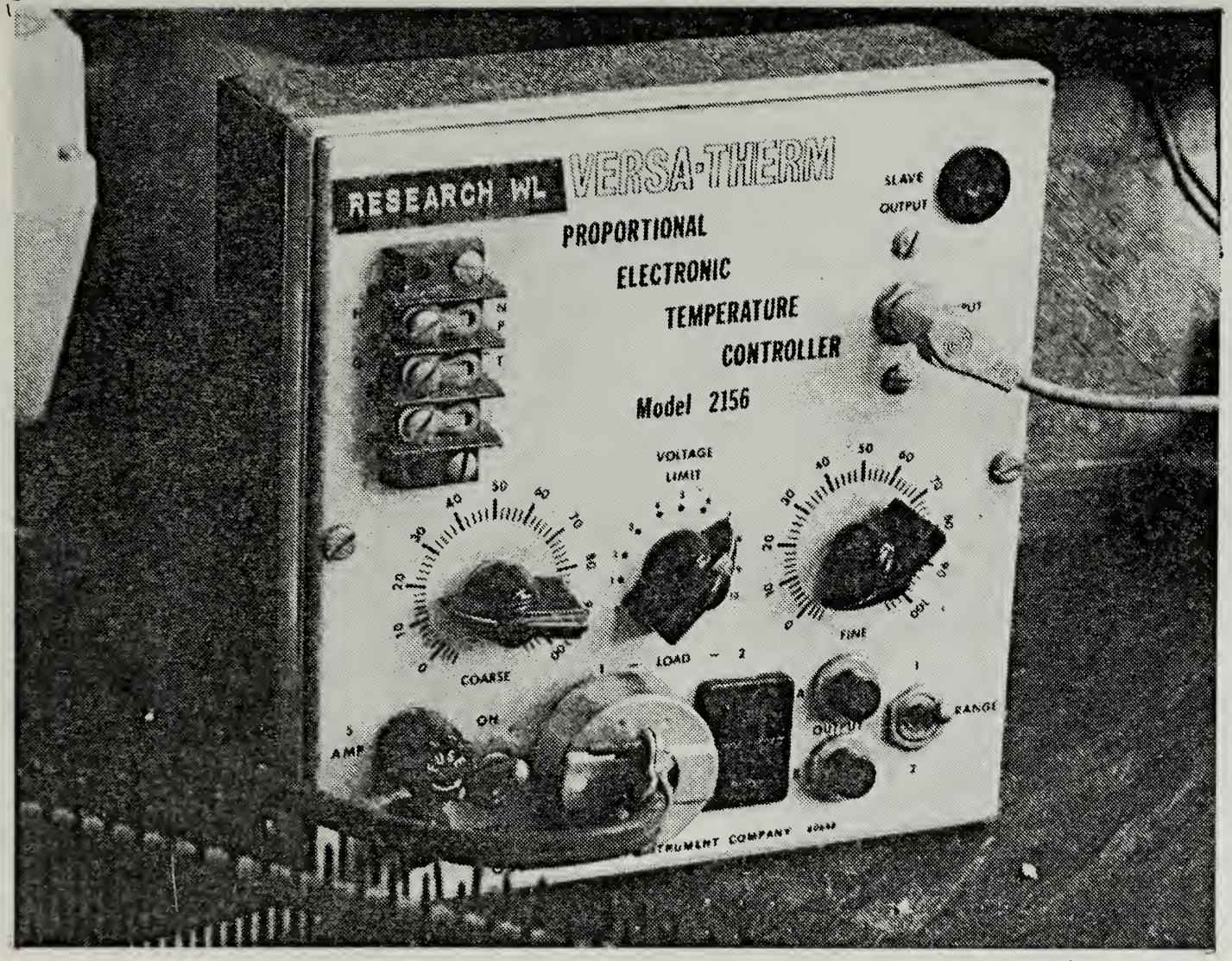


Figure 7. Versa-Therm Proportional Electronic Temperature Controller, Model 2156



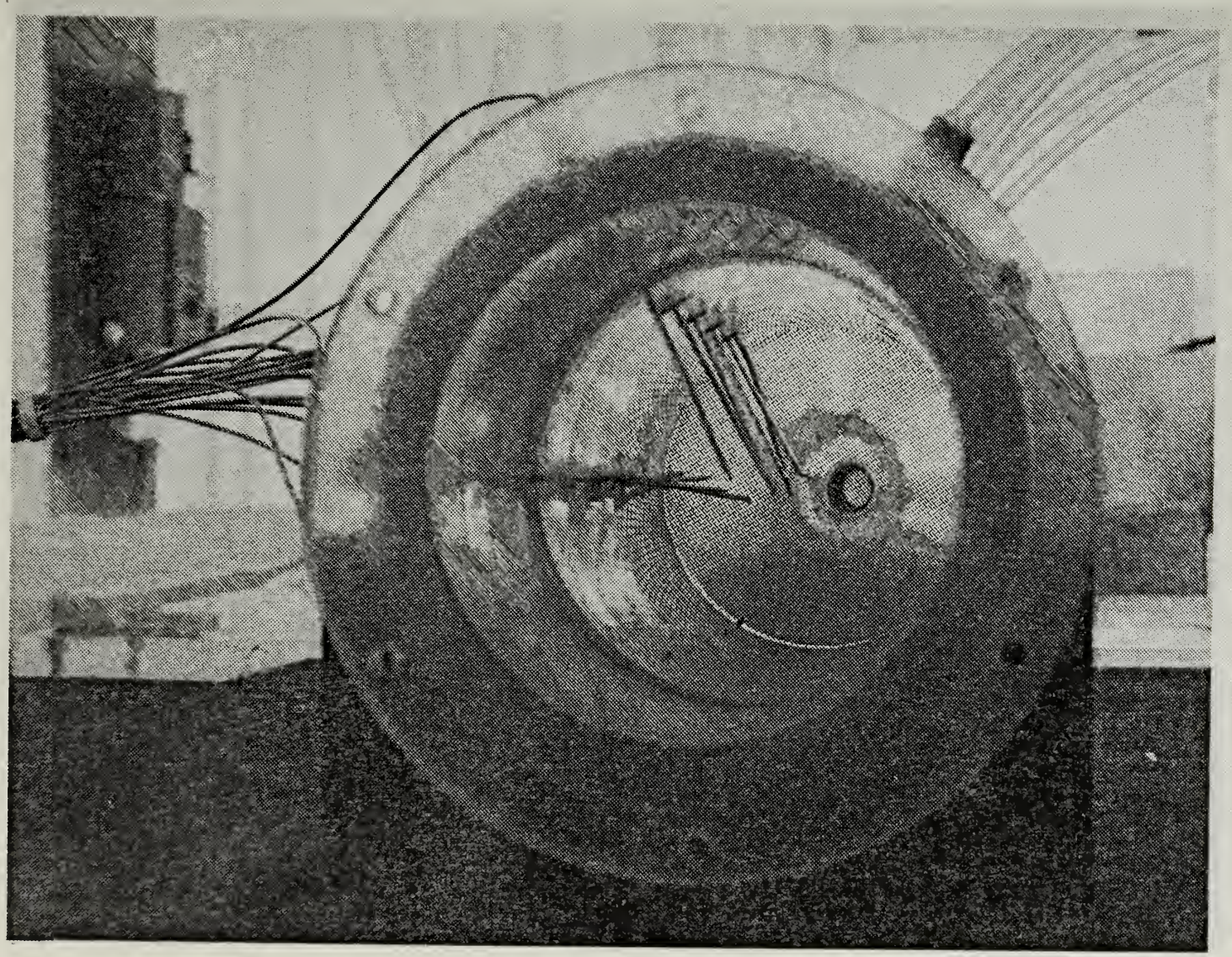


Figure 8. Variable L/D Canister.

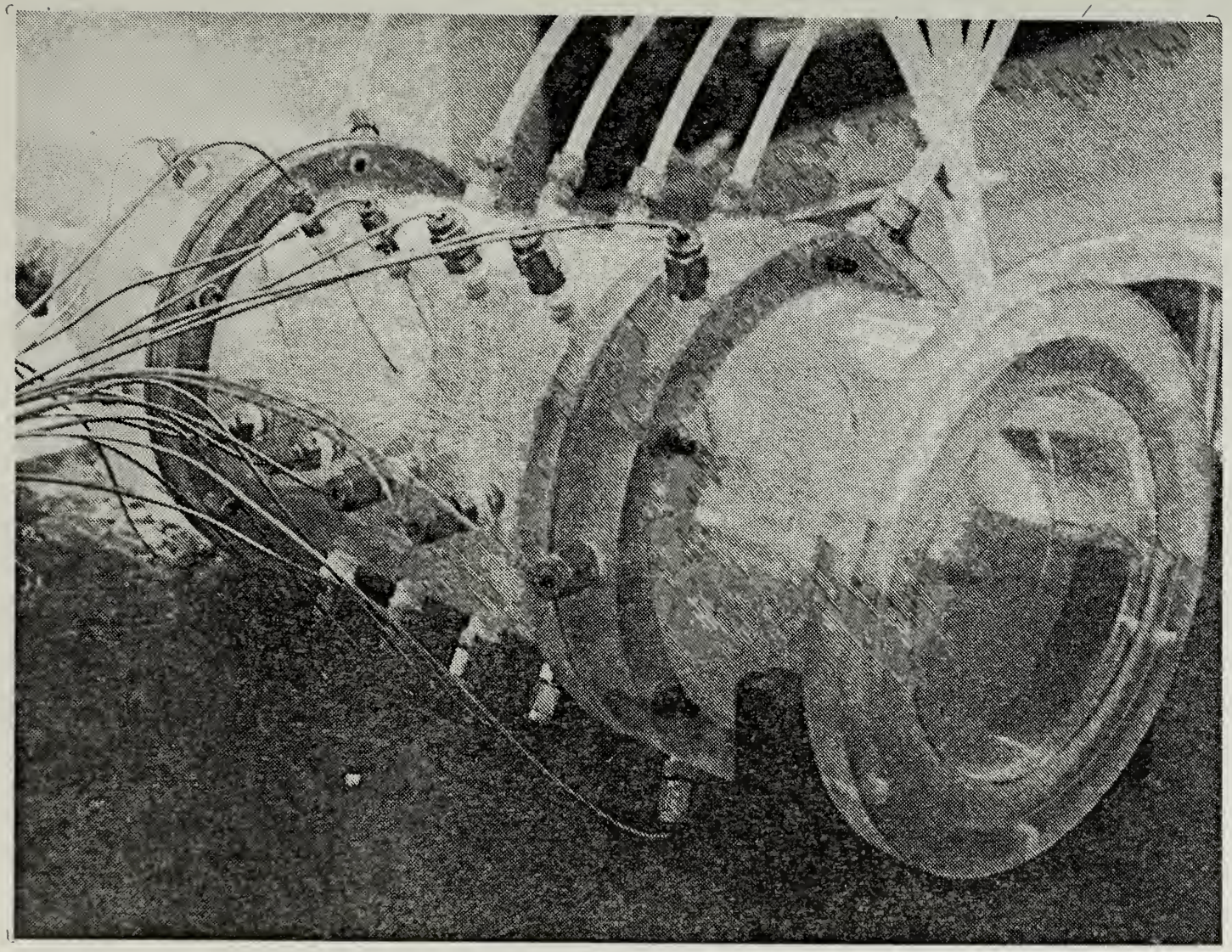


Figure 9. Variable L/D Canister External

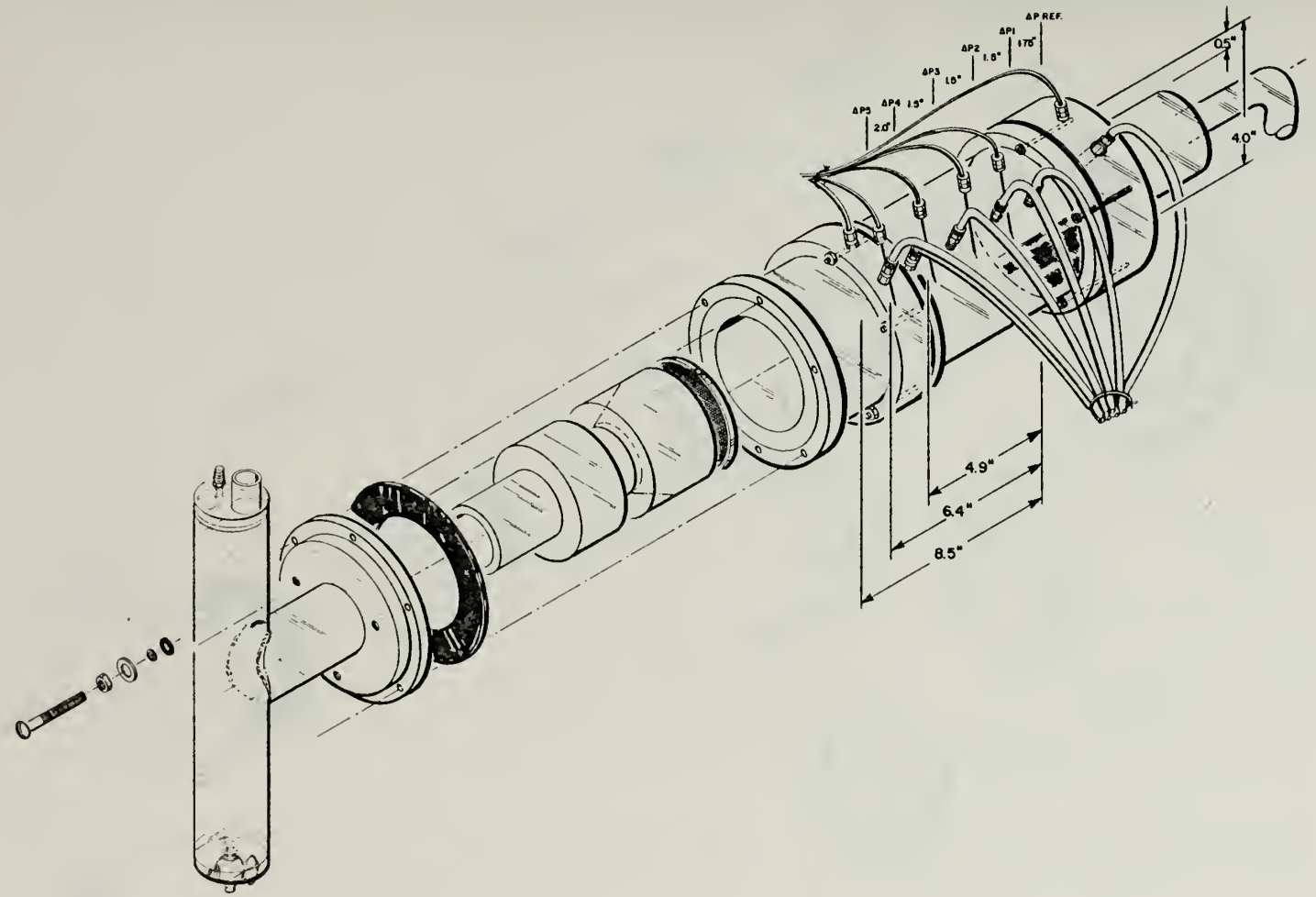


Figure 10. Variable L/D Canister Assembly with Discharge Chamber

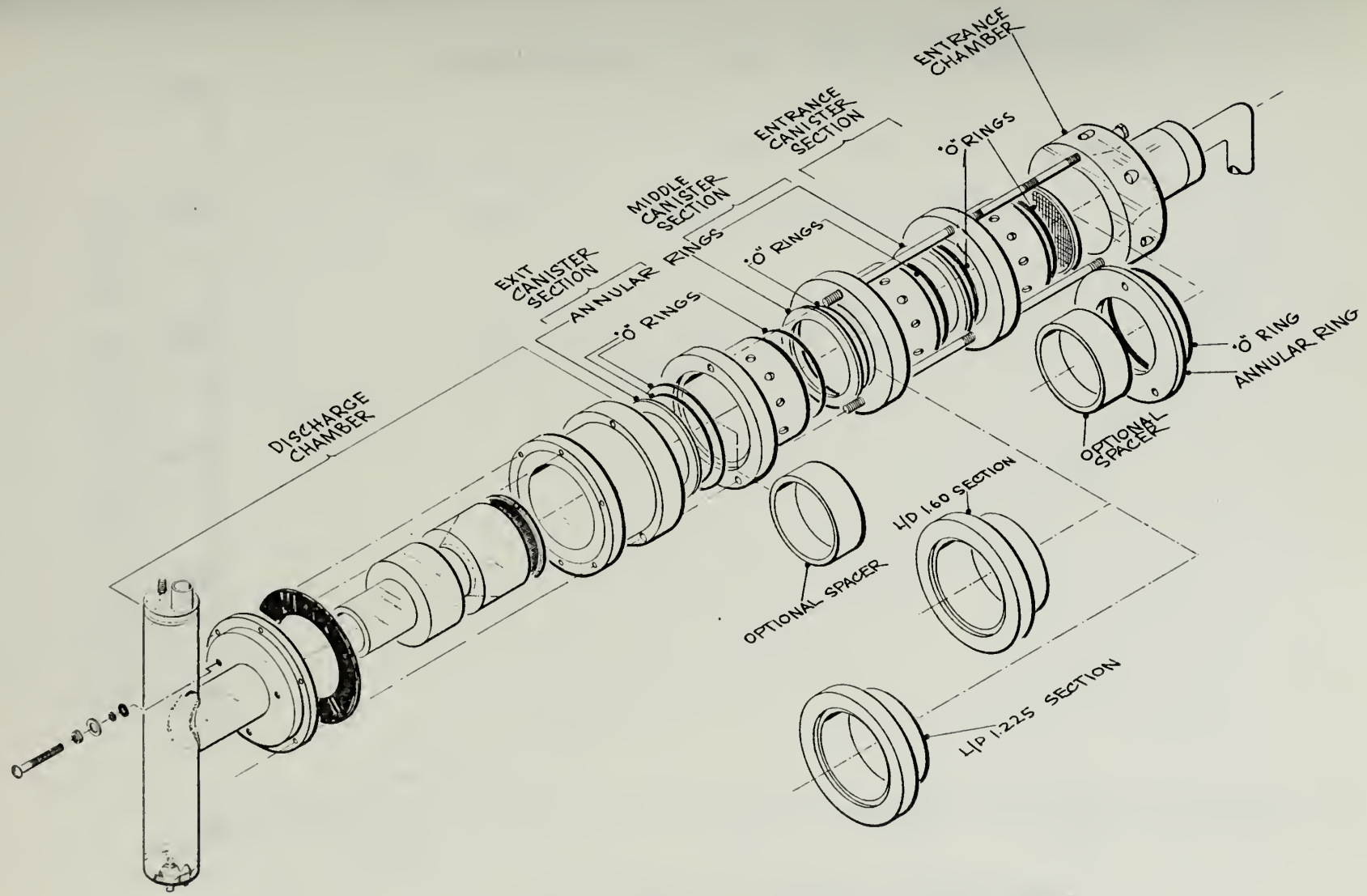


Figure 11. Variable L/D Canister with Annular Rings Assembly

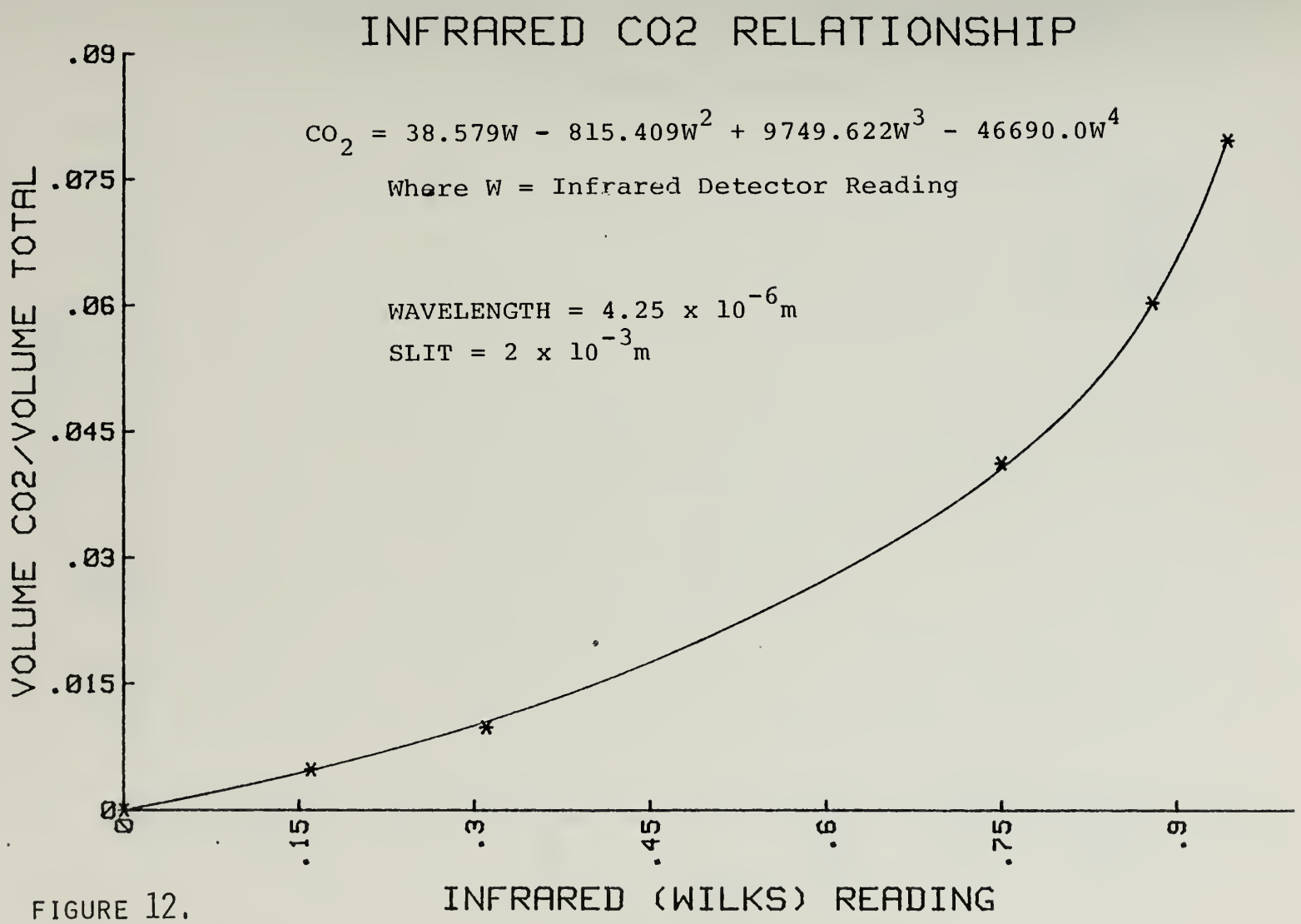

INFRARED CO2 RELATIONSHIP
$CO_2 = 38.579W - 815.409W^2 + 9749.622W^3 - 46690.0W^4$
Where W = Infrared Detector Reading
WAVELENGTH = 4.25×10^{-6}m
SLIT = 2×10^{-3}m
VOLUME CO2/VOLUME TOTAL
.09
.075
.06
.045
.03
.015
0
0
.15
.3
.45
.6
.75
.9
INFRARED (WILKS) READING

FIGURE 12.

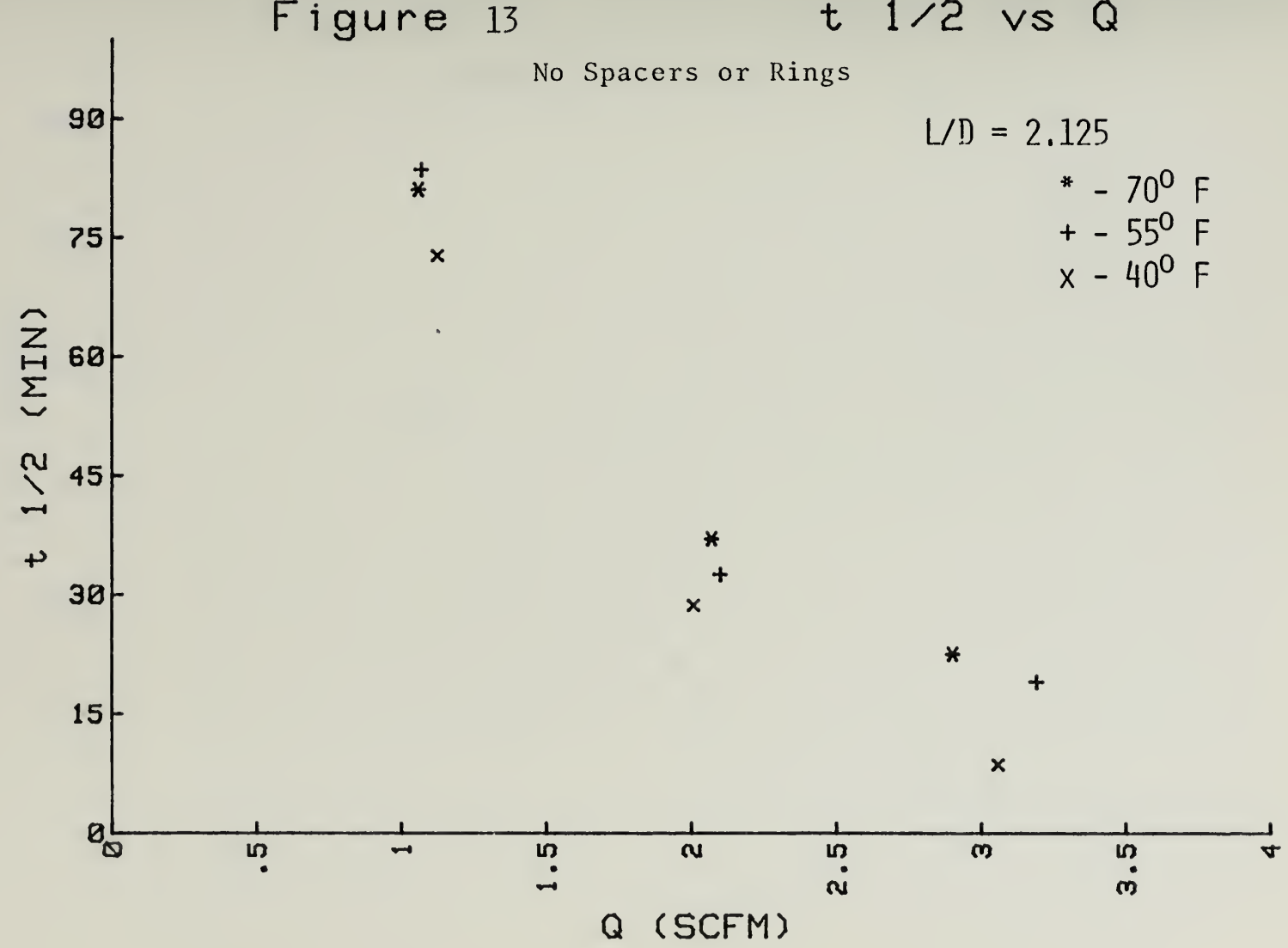

Figure 13 t 1/2 vs Q
No Spacers or Rings
L/D = 2.125
* - 70° F
+ - 55° F
x - 40° F
t 1/2 (MIN)
90
75
60
45
30
15
0
0
.5
1
1.5
2
2.5
3
3.5
4
Q (SCFM)

Figure 14 t 1/2 vs Q

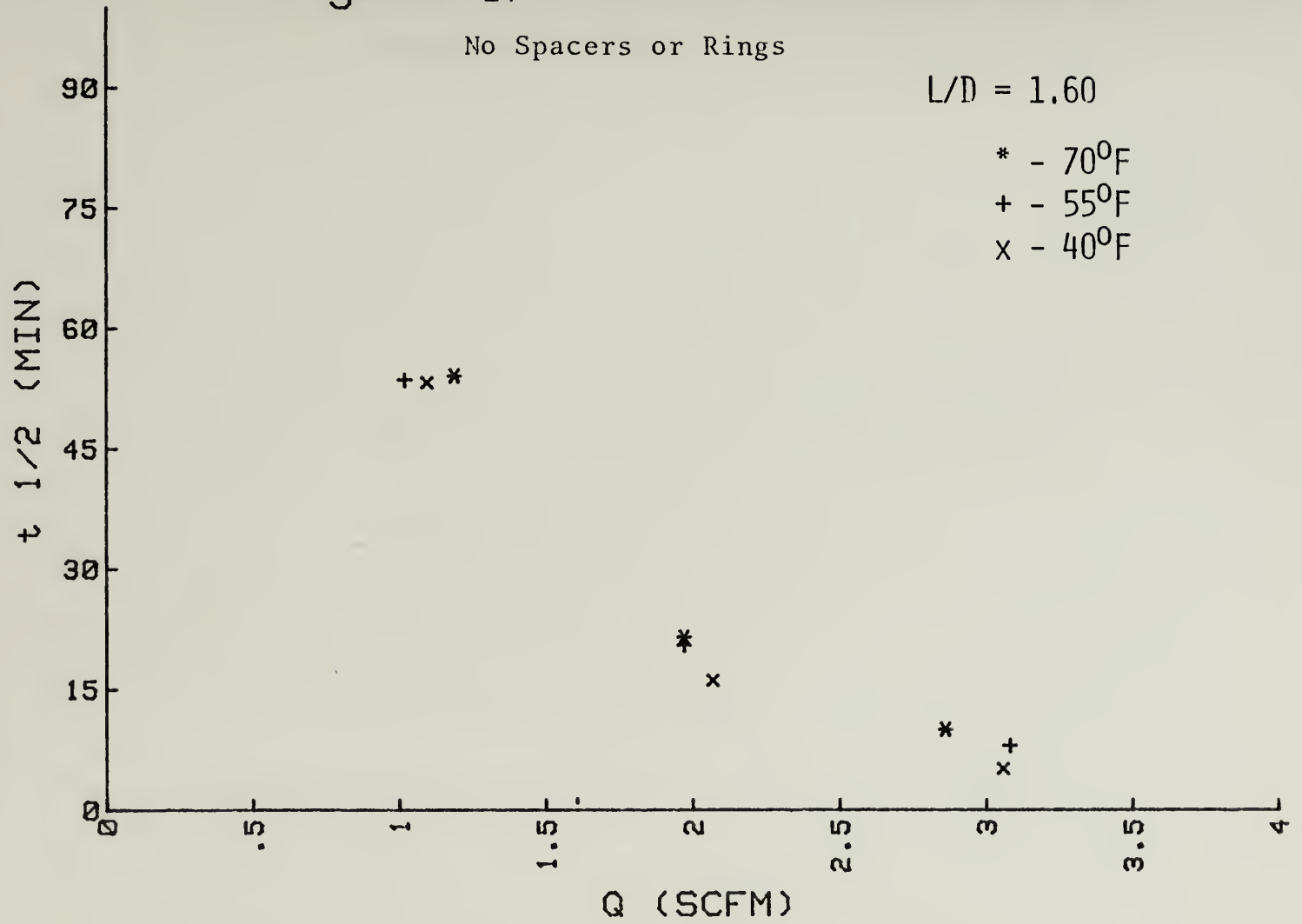
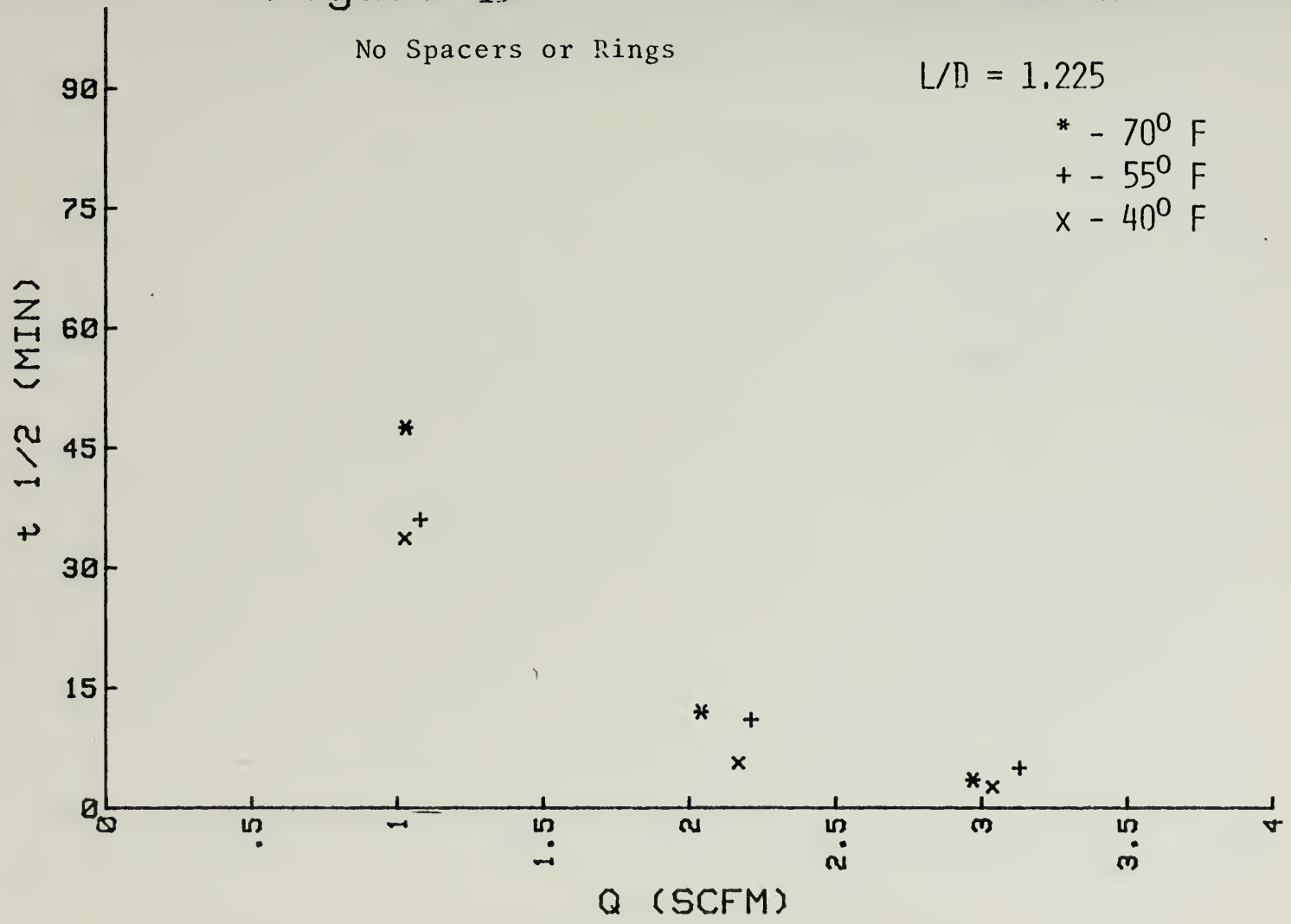


Figure 15 t 1/2 vs Q



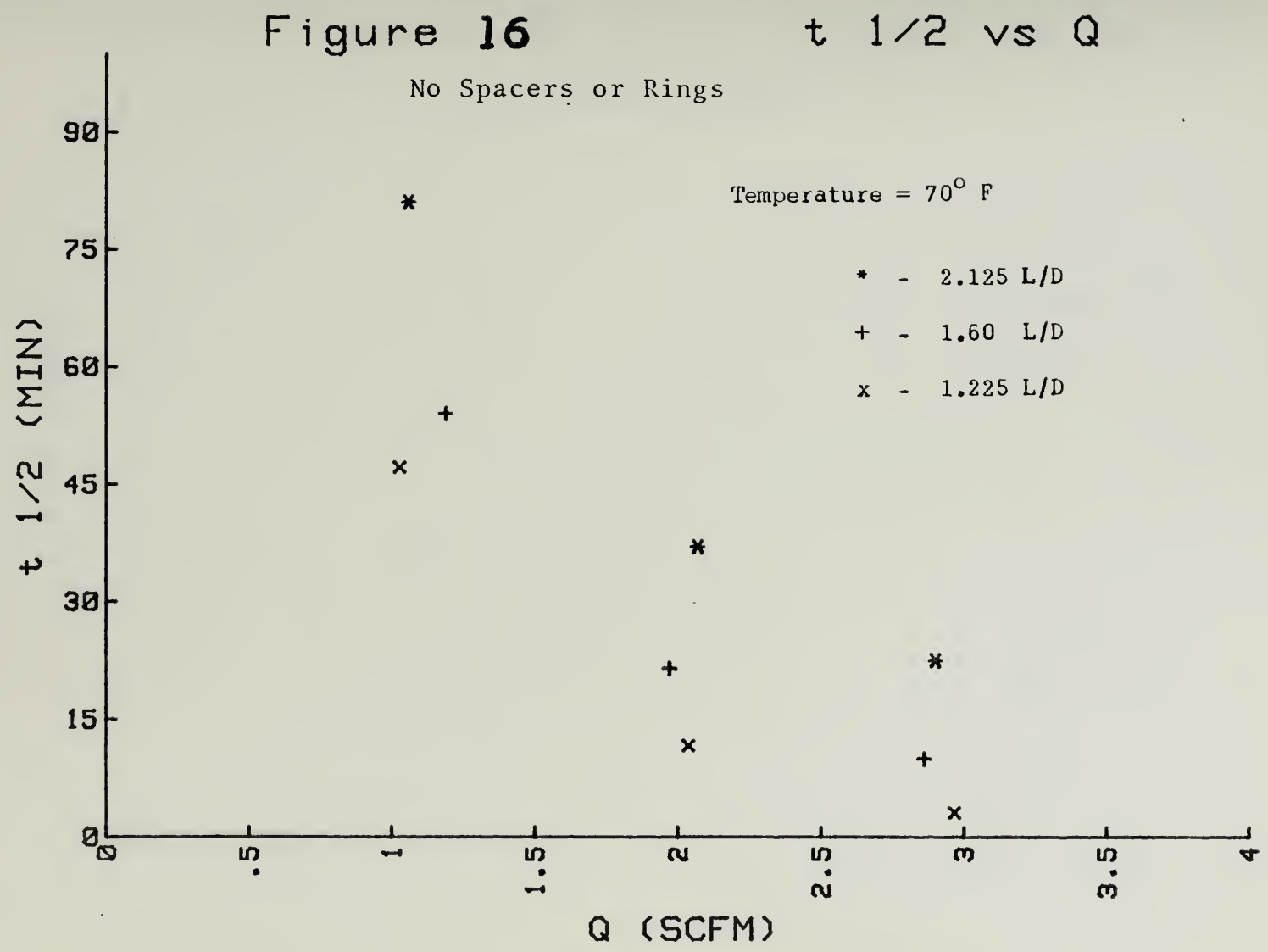

Figure 16
t 1/2 vs Q
No Spacers or Rings
Temperature = 70° F
* - 2.125 L/D
+ - 1.60 L/D
x - 1.225 L/D
t 1/2 (MIN)
90
75
60
45
30
15
0
0
.5
1
1.5
2
2.5
3
3.5
4
Q (SCFM)

Figure 17 t 1/2 vs Q

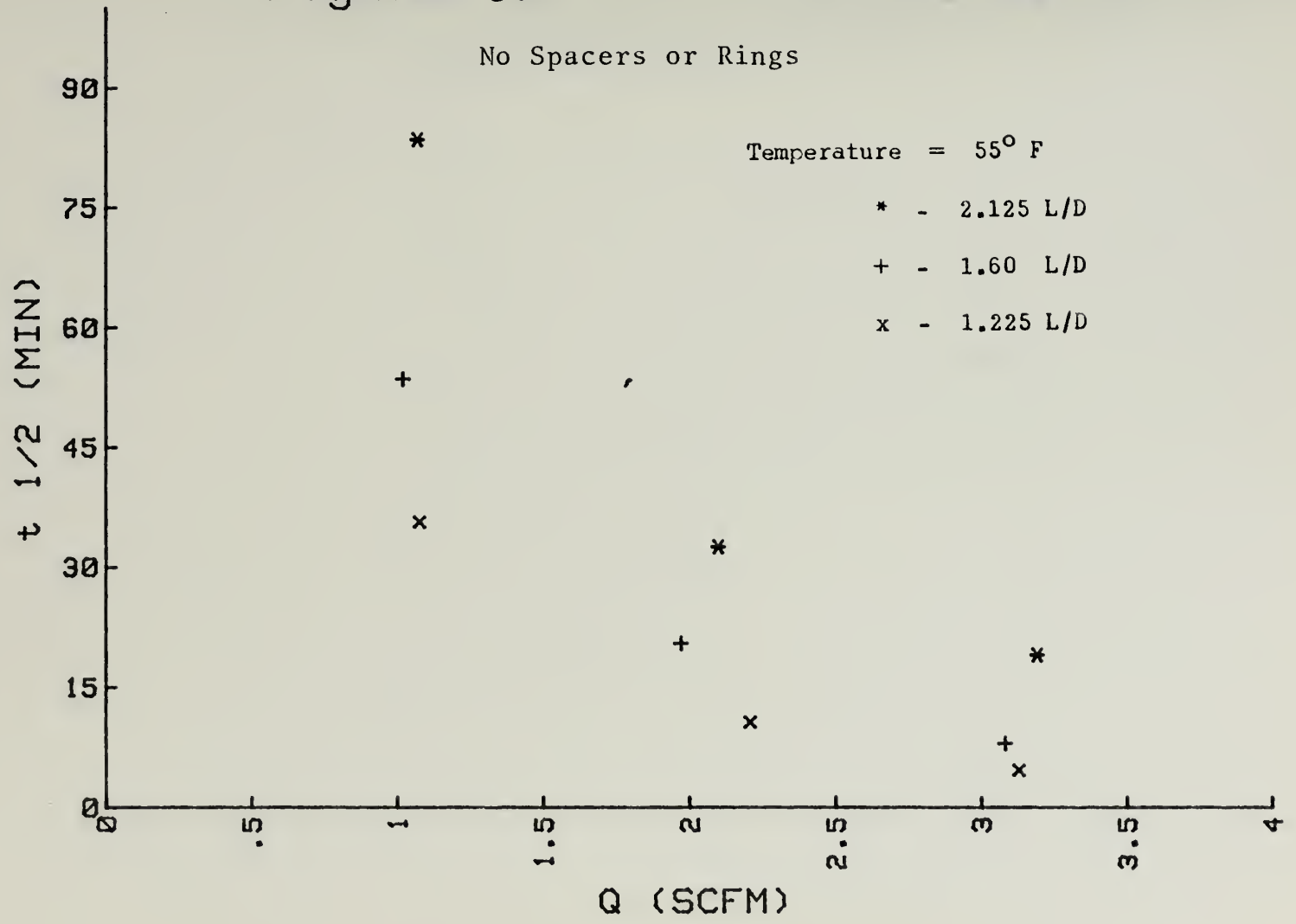


Figure 18 t 1/2 vs Q

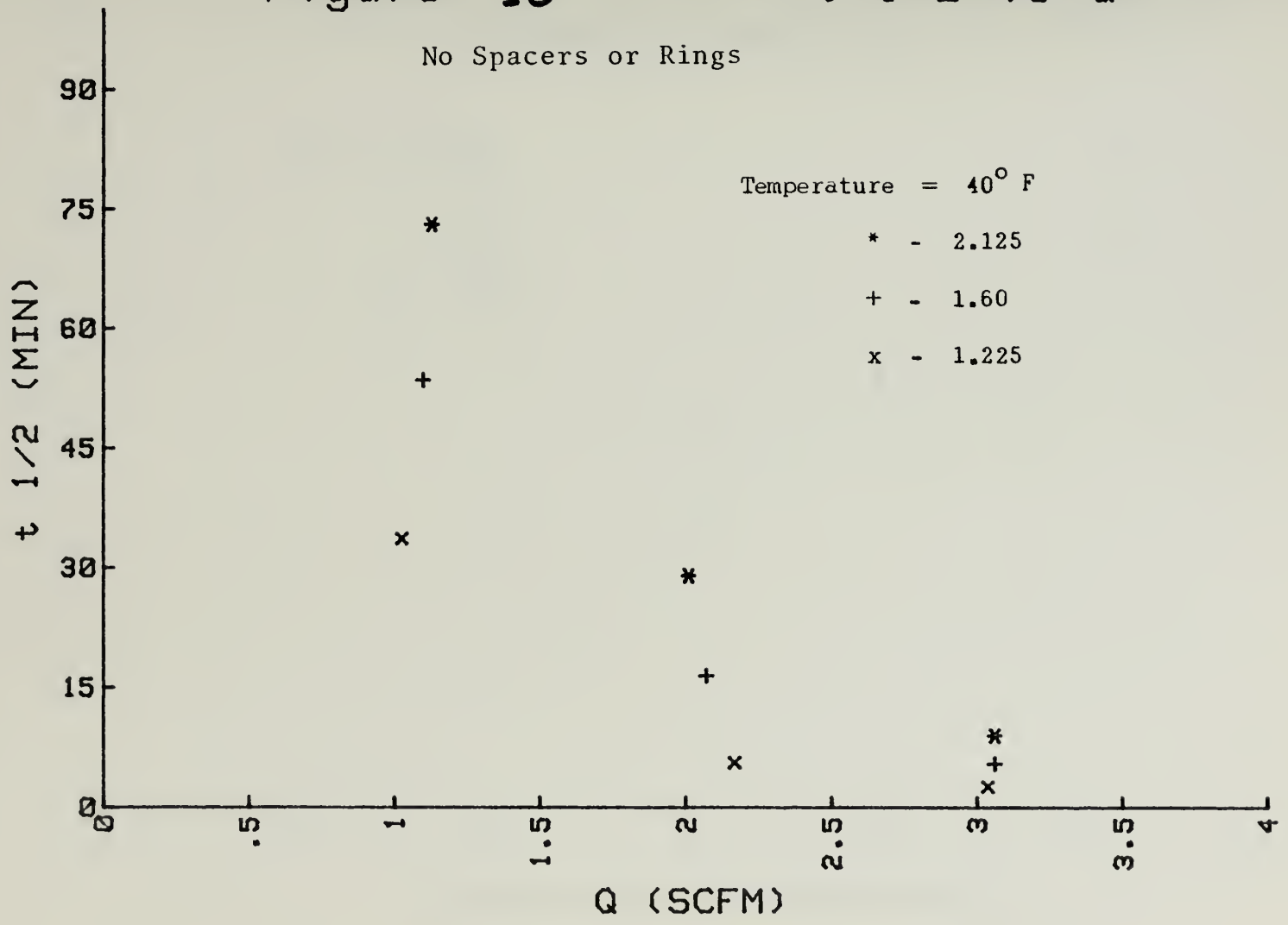
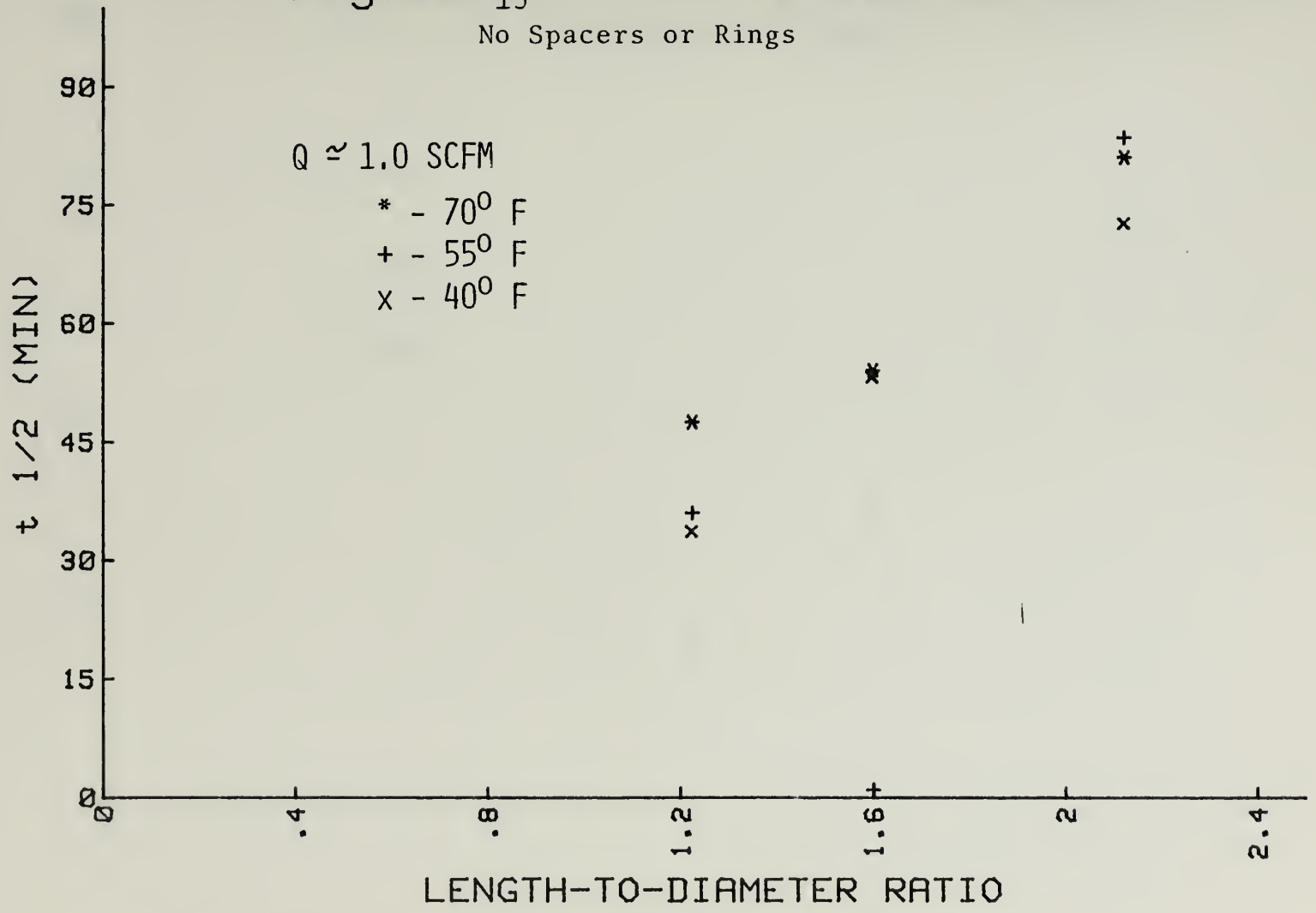
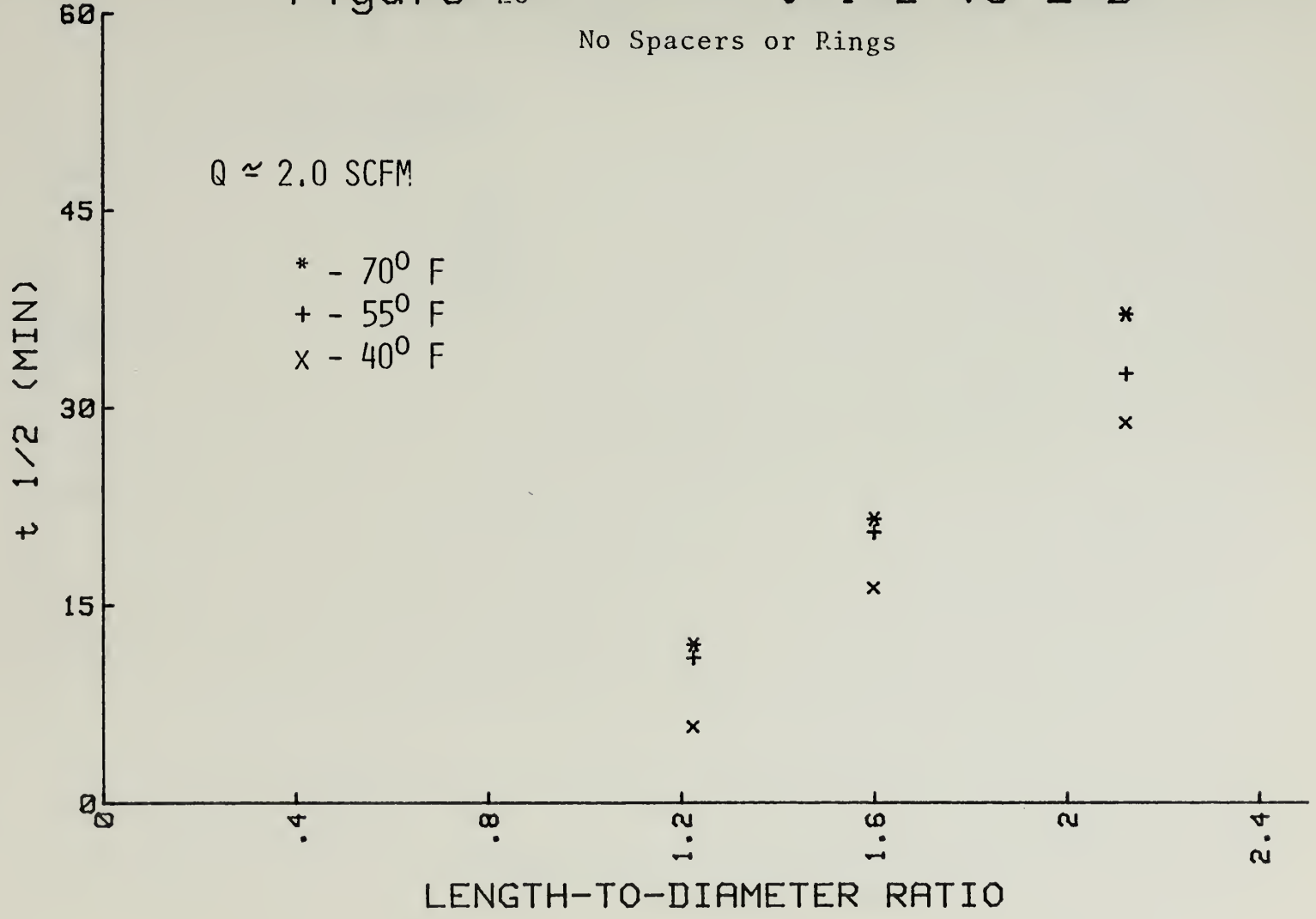
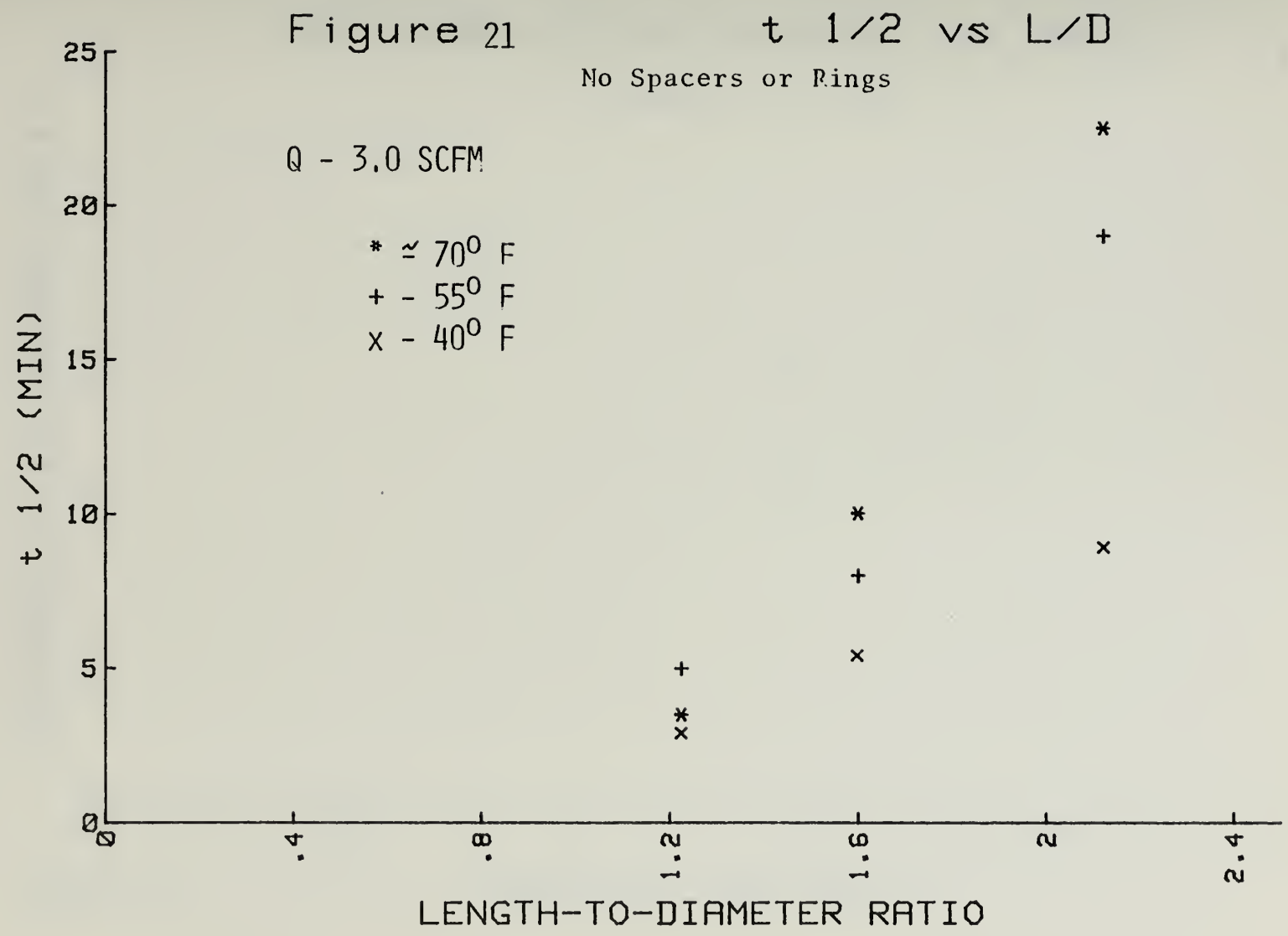


Figure 19 t 1/2 vs L/D

No Spacers or Rings




Figure 20 t 1/2 vs L/D
No Spacers or Rings
Q ≃ 2.0 SCFM
* - 70° F
+ - 55° F
x - 40° F
t 1/2 (MIN)
60
45
30
15
0
0
.4
.8
1.2
1.6
2
2.4
LENGTH-TO-DIAMETER RATIO


Figure 21
t 1/2 vs L/D
No Spacers or Rings
Q - 3.0 SCFM
* ≃ 70° F
+ - 55° F
x - 40° F
t 1/2 (MIN)
25
20
15
10
5
0
0
.4
.8
1.2
1.6
2
2.4
LENGTH-TO-DIAMETER RATIO

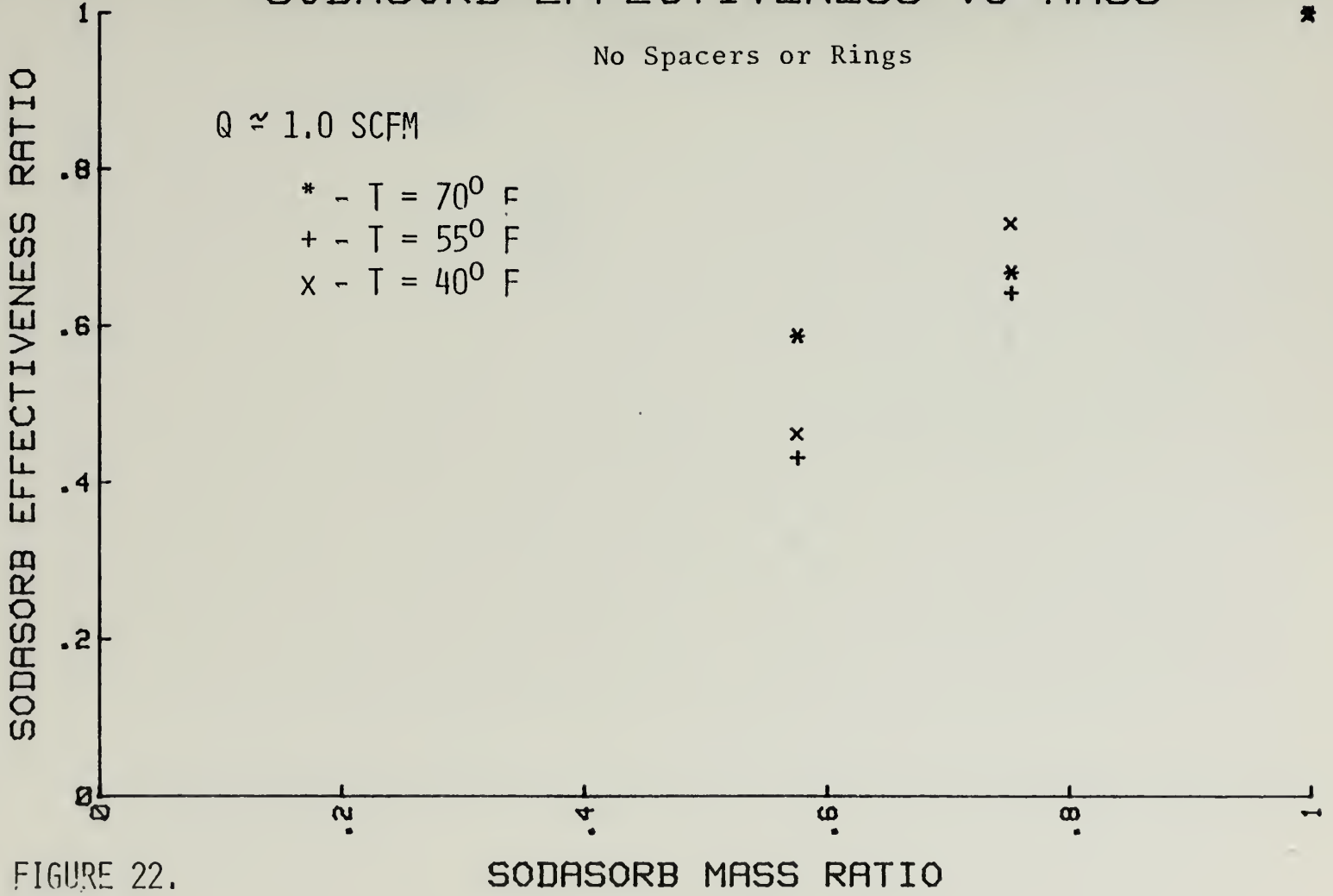

SODASORB EFFECTIVENESS vs MASS
No Spacers or Rings
Q ≈ 1.0 SCFM
* - T = 70° F
+ - T = 55° F
x - T = 40° F
SODASORB EFFECTIVENESS RATIO
SODASORB MASS RATIO
0
.2
.4
.6
.8
1

FIGURE 22.

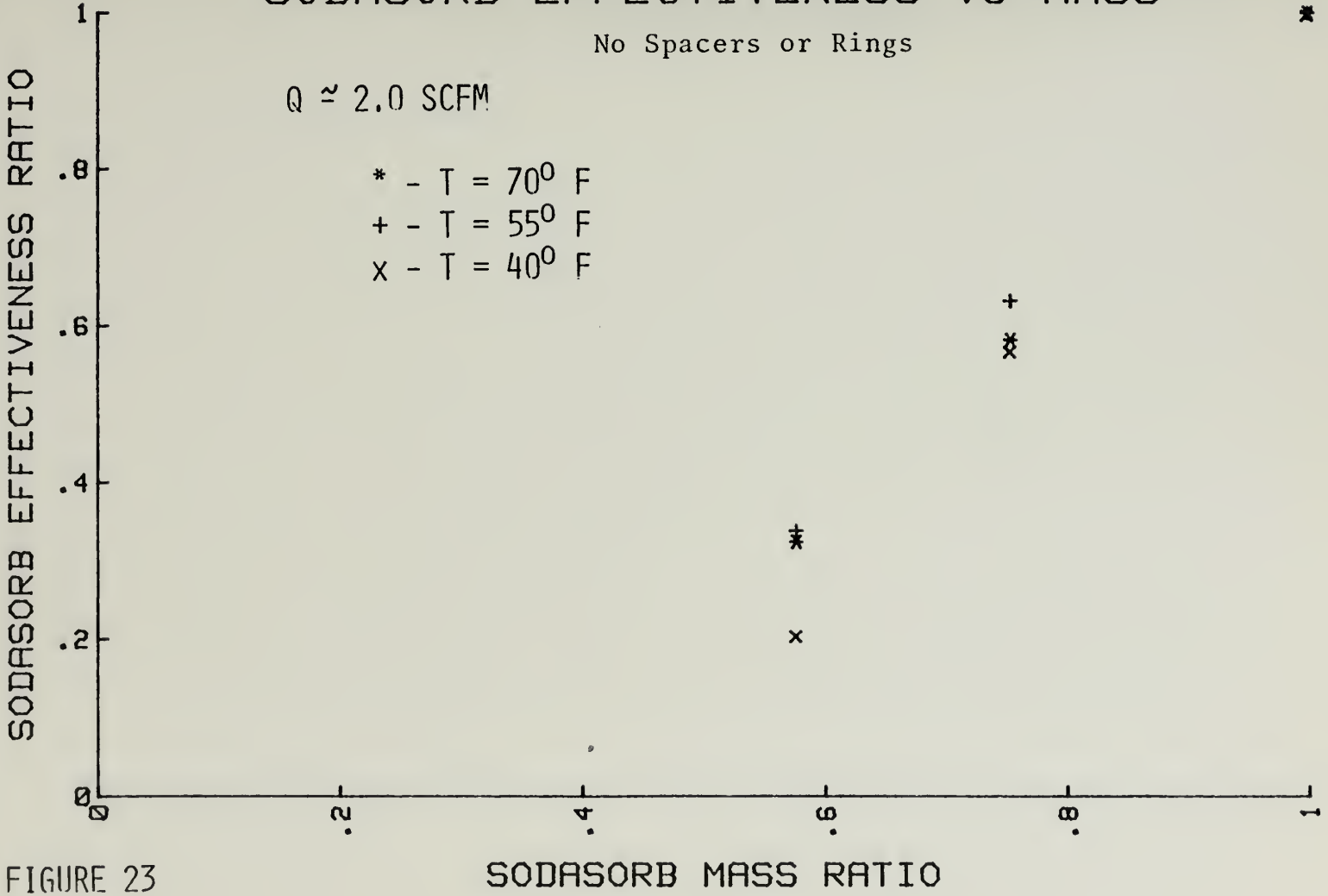

SODASORB EFFECTIVENESS vs MASS
No Spacers or Rings
Q ≃ 2.0 SCFM
* - T = 70° F
+ - T = 55° F
x - T = 40° F
SODASORB EFFECTIVENESS RATIO
SODASORB MASS RATIO
0
.2
.4
.6
.8
1

FIGURE 23

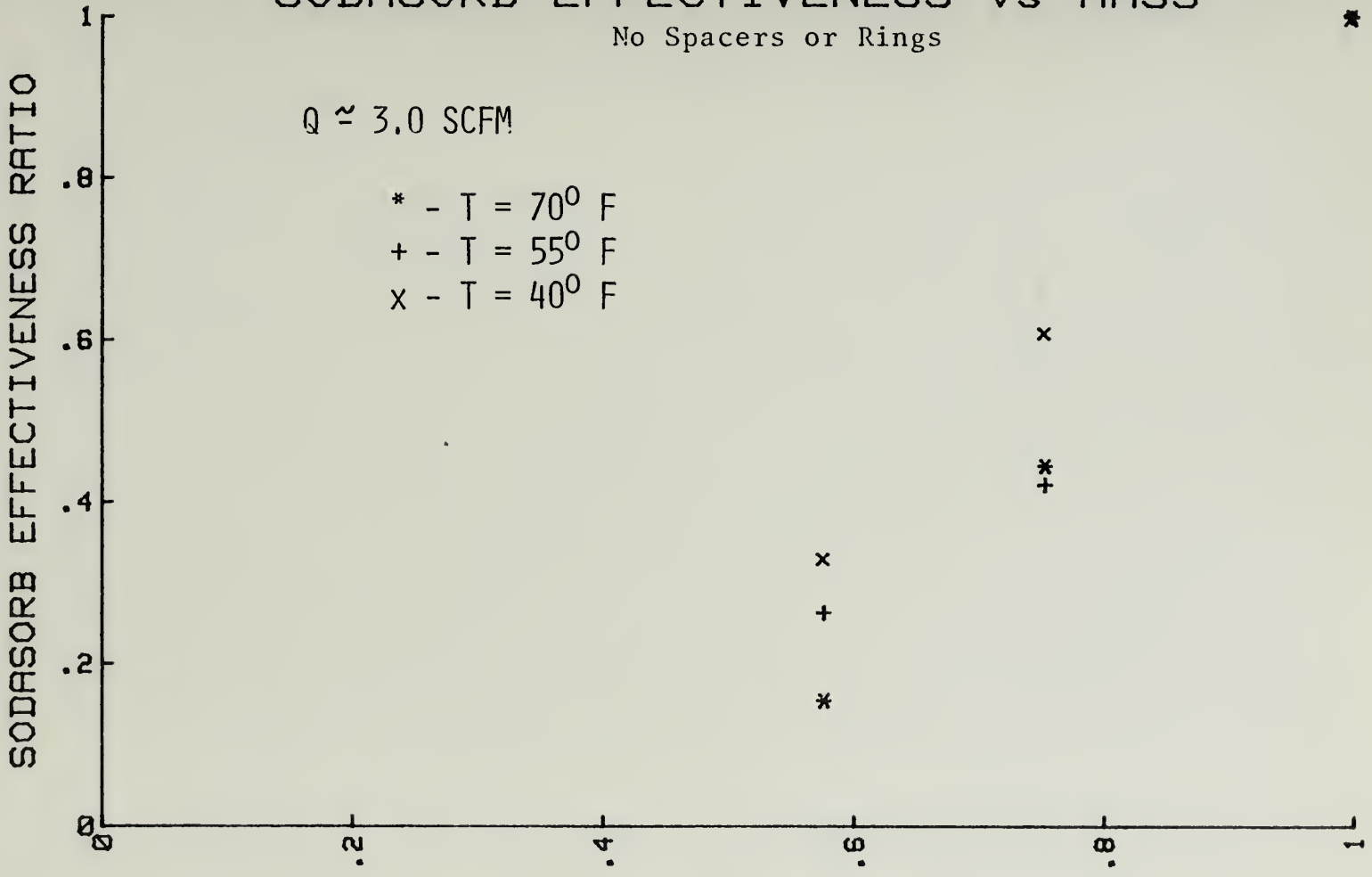

SODASORB EFFECTIVENESS vs MASS
No Spacers or Rings
Q ≃ 3.0 SCFM
* - T = 70° F
+ - T = 55° F
x - T = 40° F
SODASORB EFFECTIVENESS RATIO
SODASORB MASS RATIO
0
.2
.4
.6
.8
1

FIGURE 24

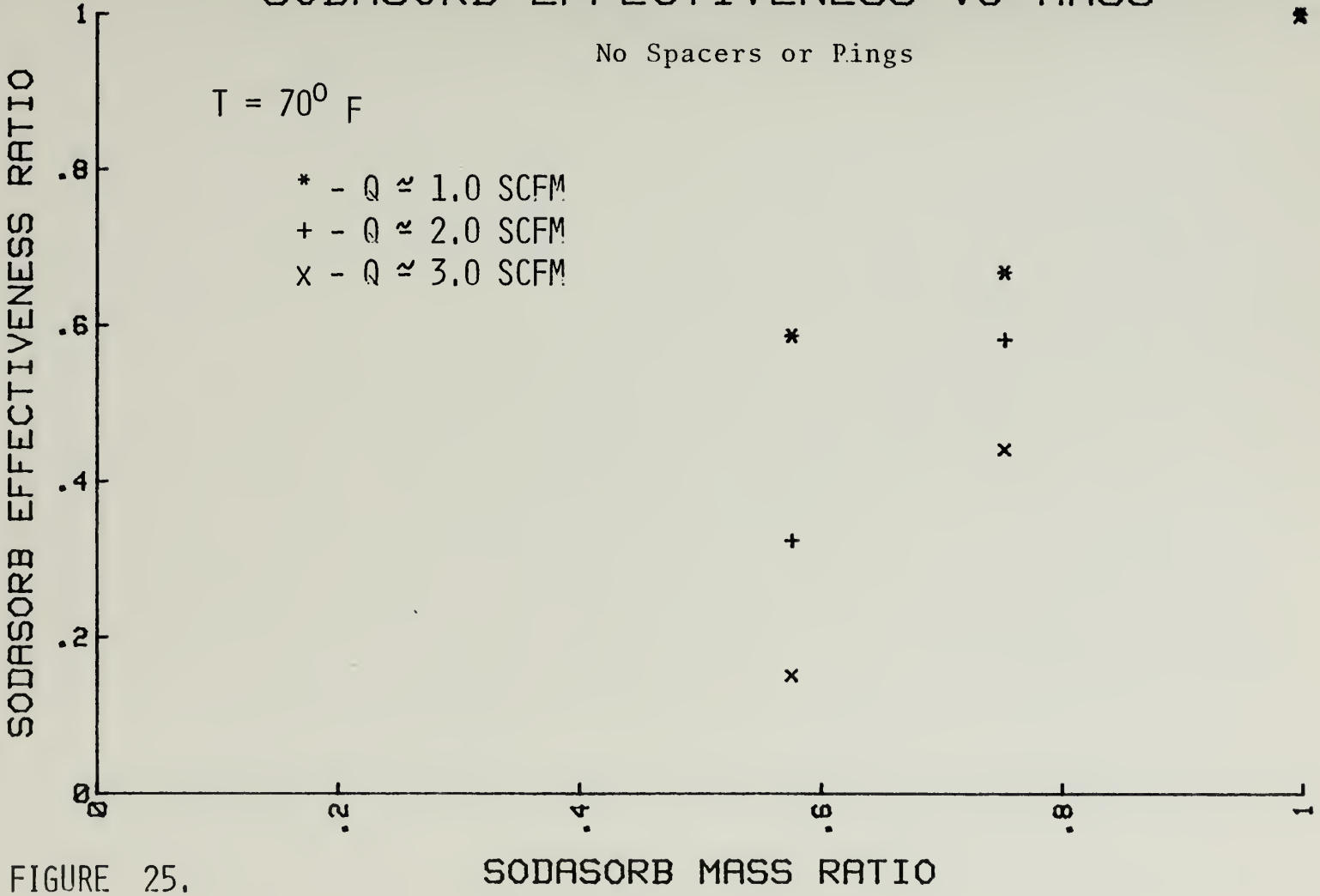

SODASORB EFFECTIVENESS vs MASS
No Spacers or Rings
T = 70° F
* - Q ≃ 1.0 SCFM
+ - Q ≃ 2.0 SCFM
x - Q ≃ 3.0 SCFM
SODASORB EFFECTIVENESS RATIO
SODASORB MASS RATIO
0
.2
.4
.6
.8
1

FIGURE 25.

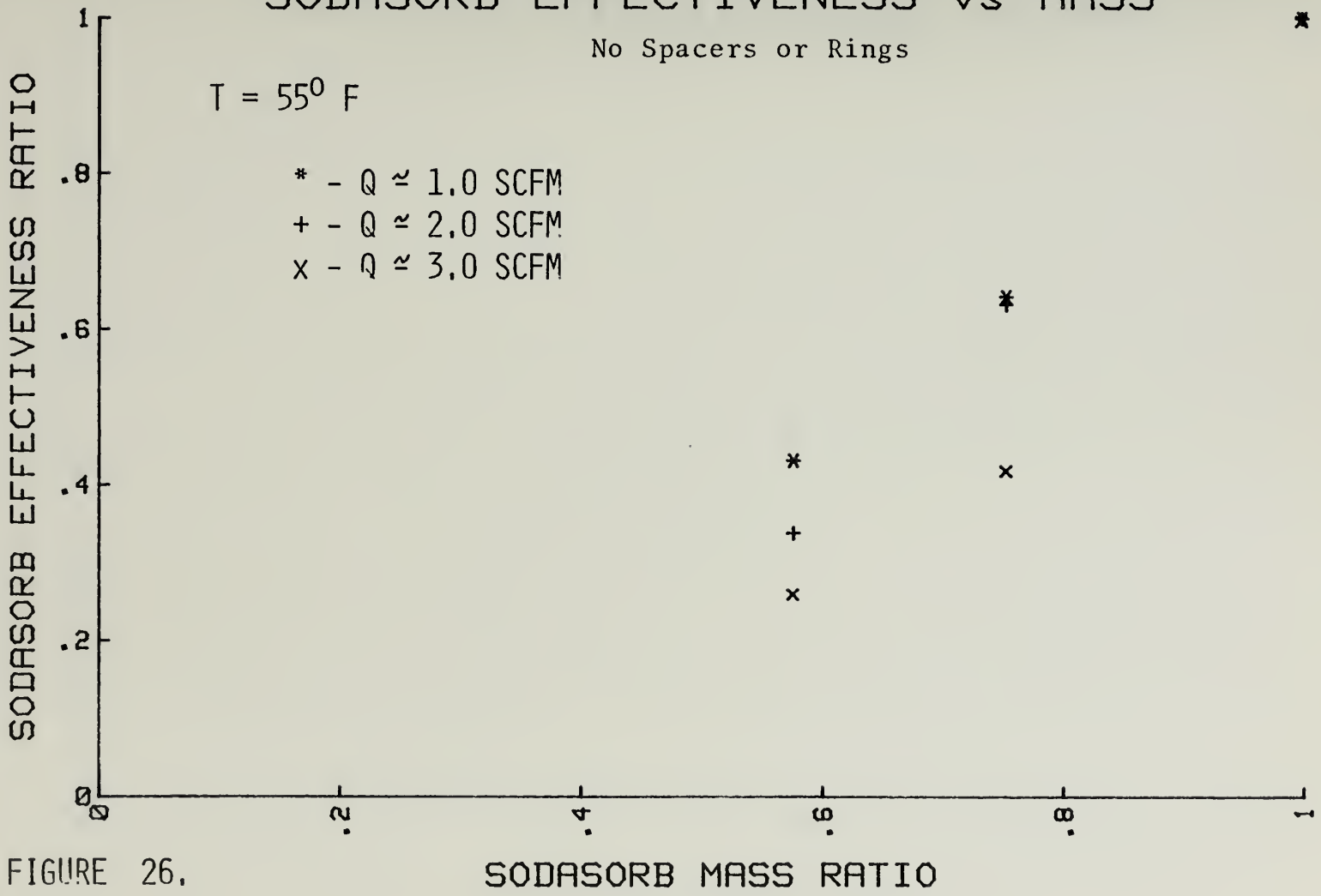

SODASORB EFFECTIVENESS vs MASS
No Spacers or Rings
T = 55° F
* - Q ≃ 1.0 SCFM
+ - Q ≃ 2.0 SCFM
x - Q ≃ 3.0 SCFM
SODASORB EFFECTIVENESS RATIO
SODASORB MASS RATIO
0
.2
.4
.6
.8
1

FIGURE 26.

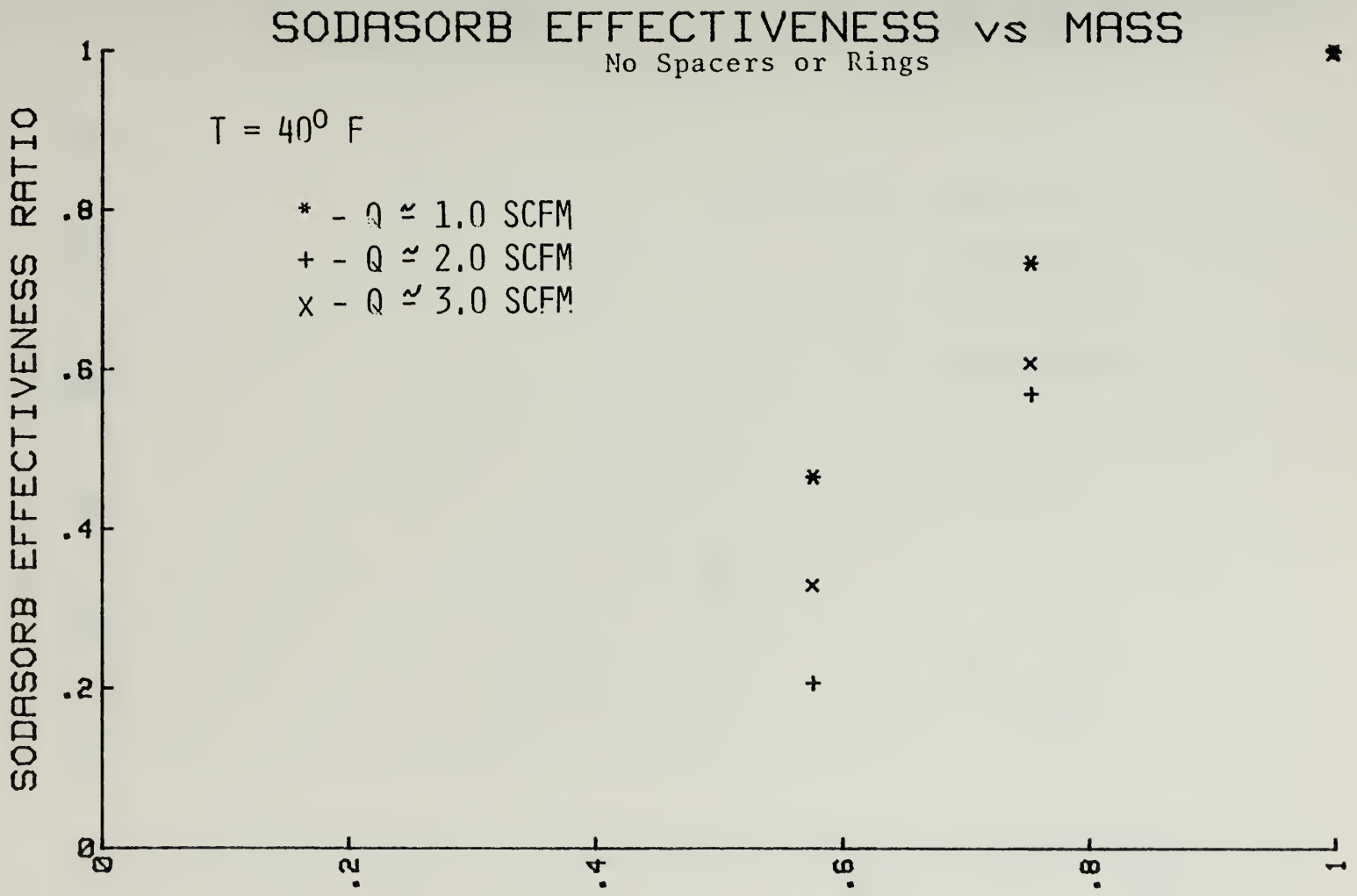
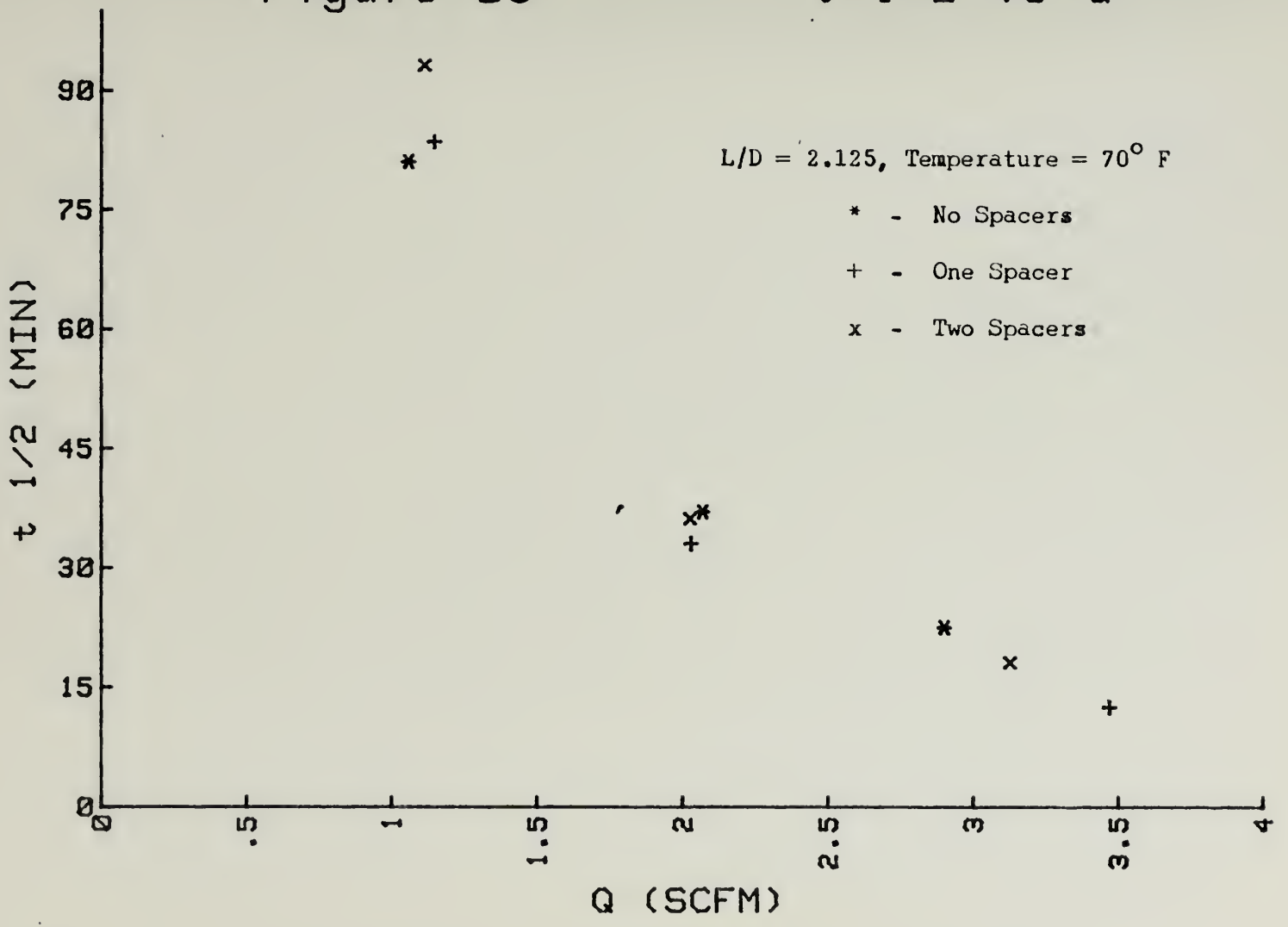

SODASORB EFFECTIVENESS vs MASS
No Spacers or Rings
T = 40° F
* - Q ≃ 1.0 SCFM
+ - Q ≃ 2.0 SCFM
x - Q ≃ 3.0 SCFM
SODASORB EFFECTIVENESS RATIO
SODASORB MASS RATIO
0
.2
.4
.6
.8
1

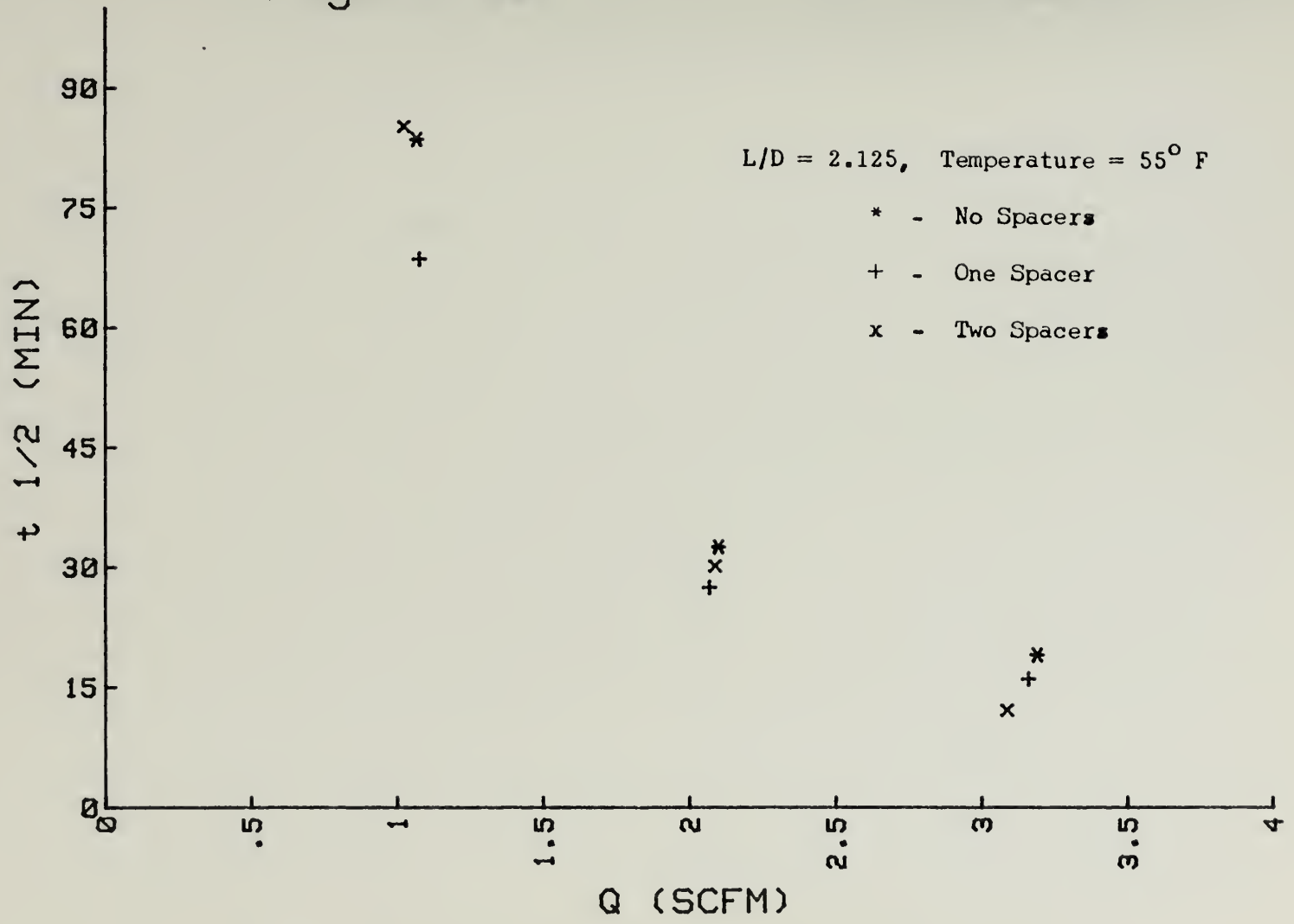
FIGURE 27

Figure 28 t 1/2 vs Q



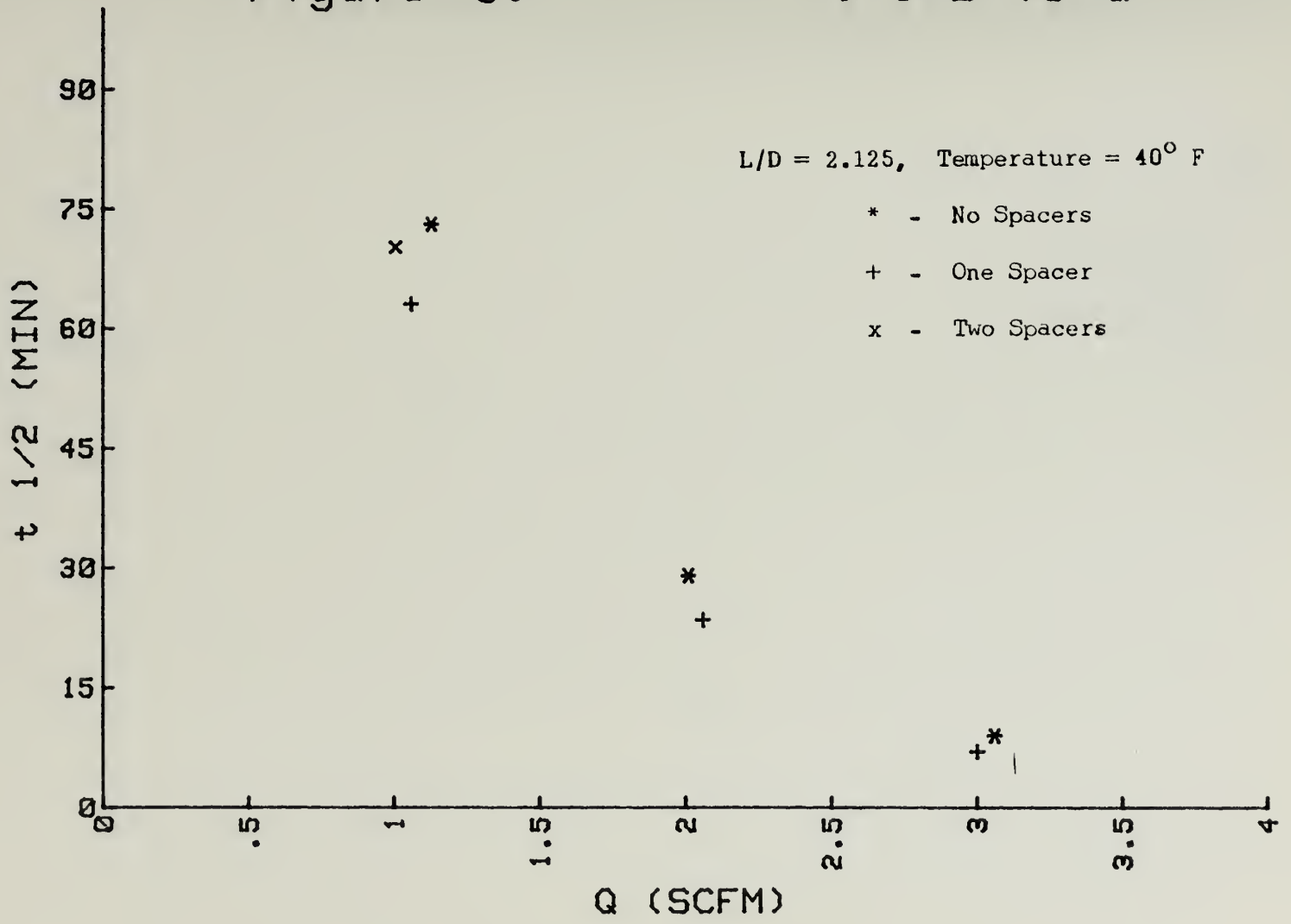
Comparison of Canisters With and Without Spacers

Figure 29 t 1/2 vs Q



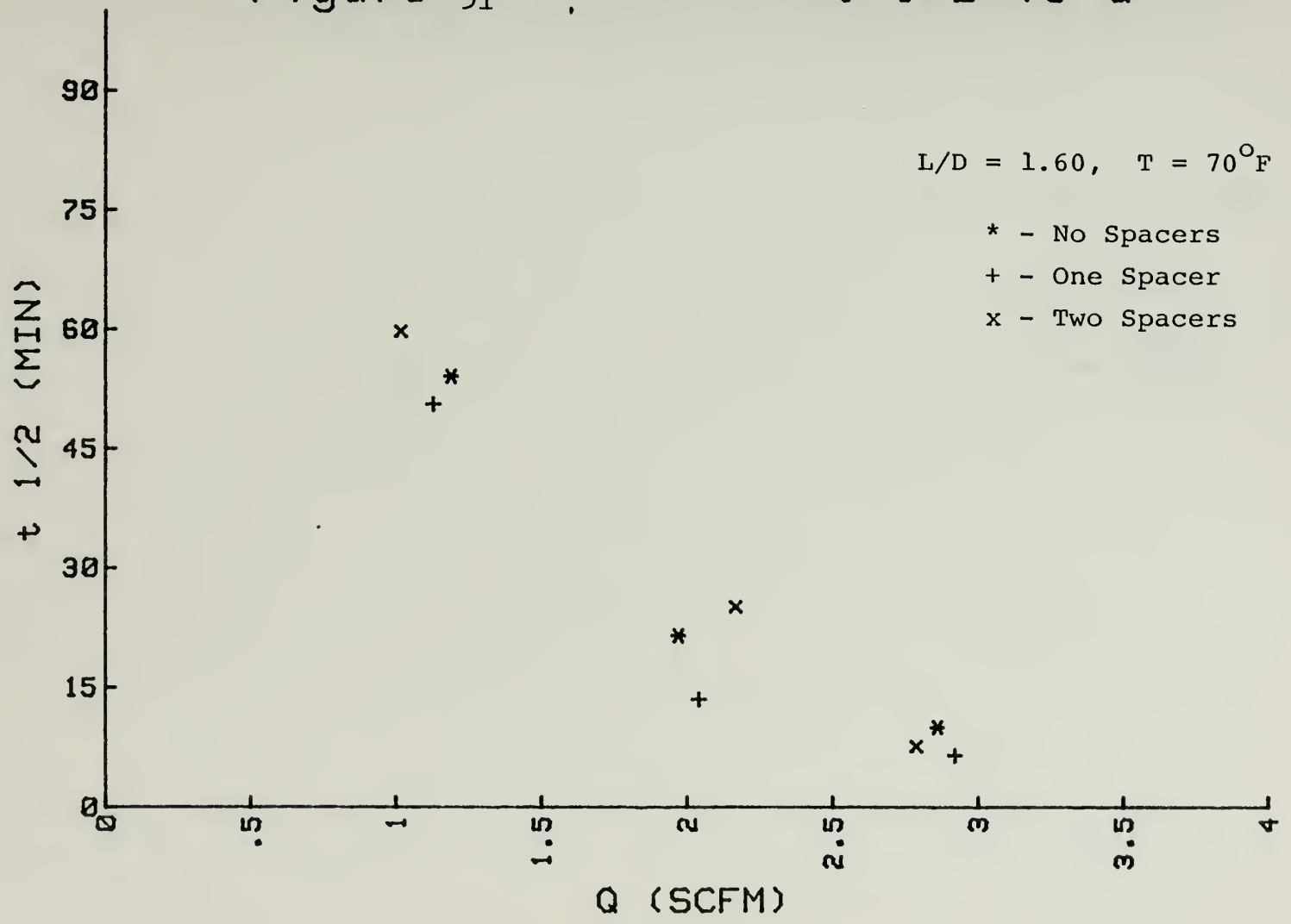
Comparison of Canisters With and Without Spacers

Figure 30 t 1/2 vs Q



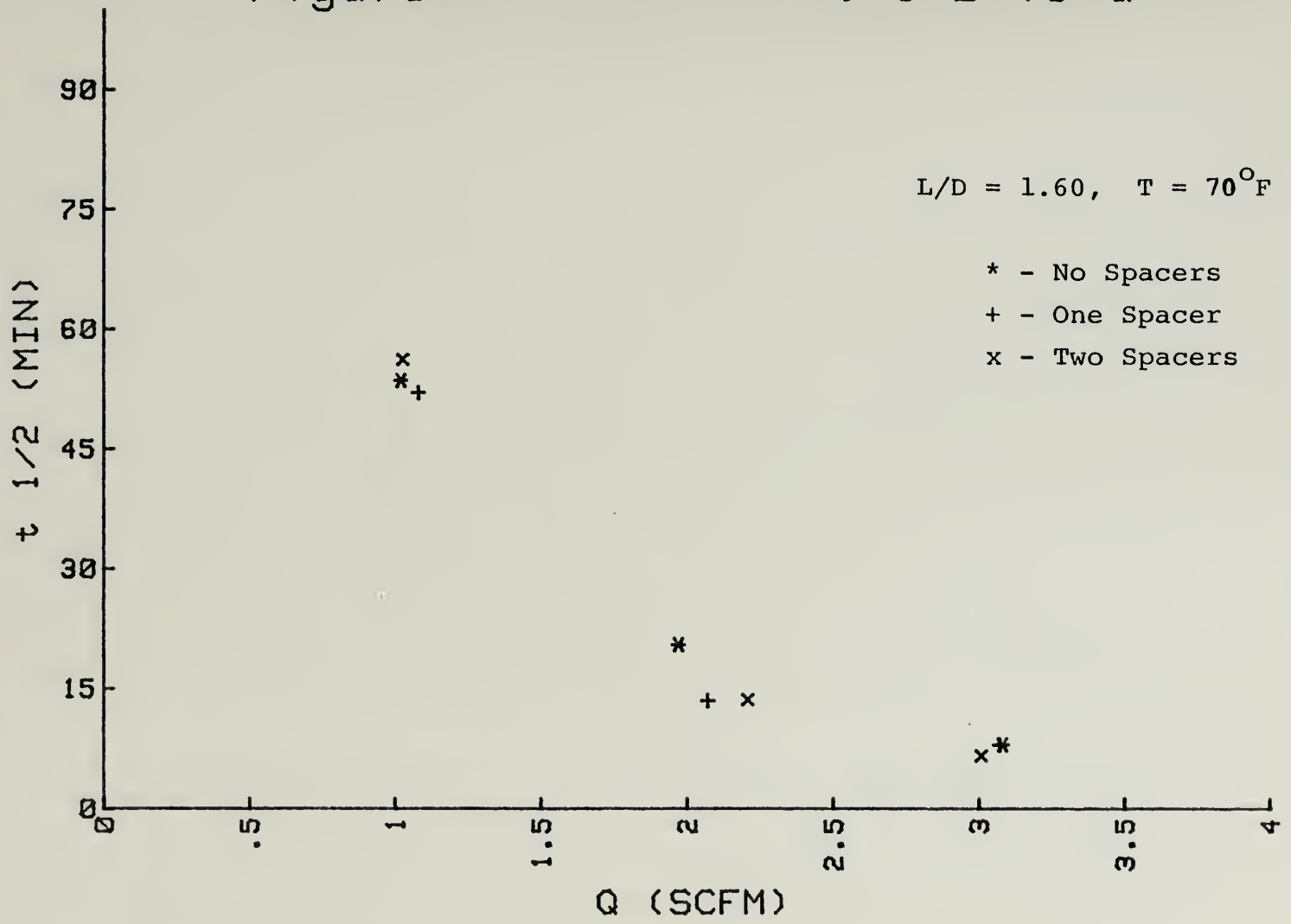
Comparison of Canisters With and Without Spacers

Figure 31 t 1/2 vs Q



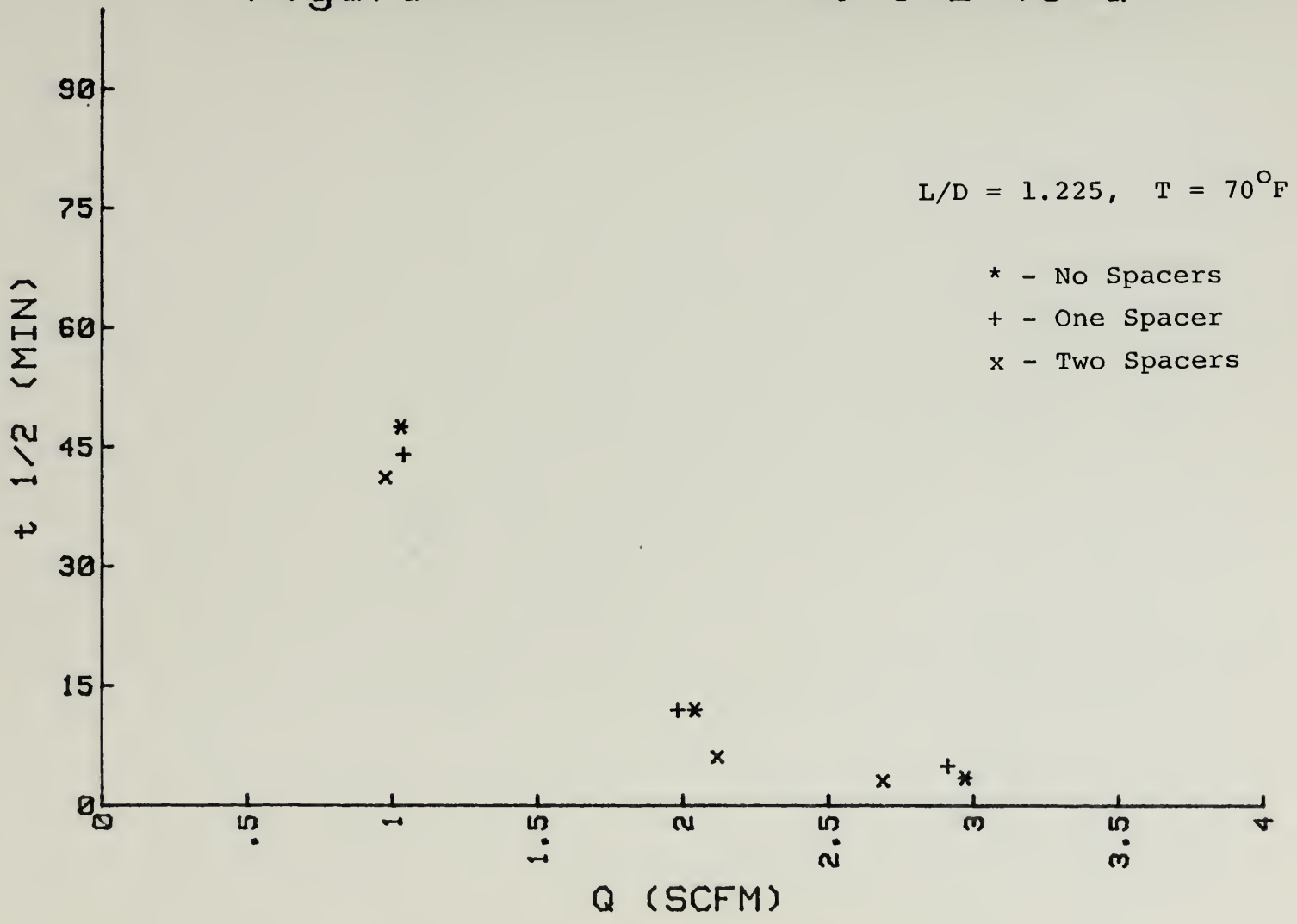
Comparison of Canisters With and Without Spacers

Figure 32 t 1/2 vs Q



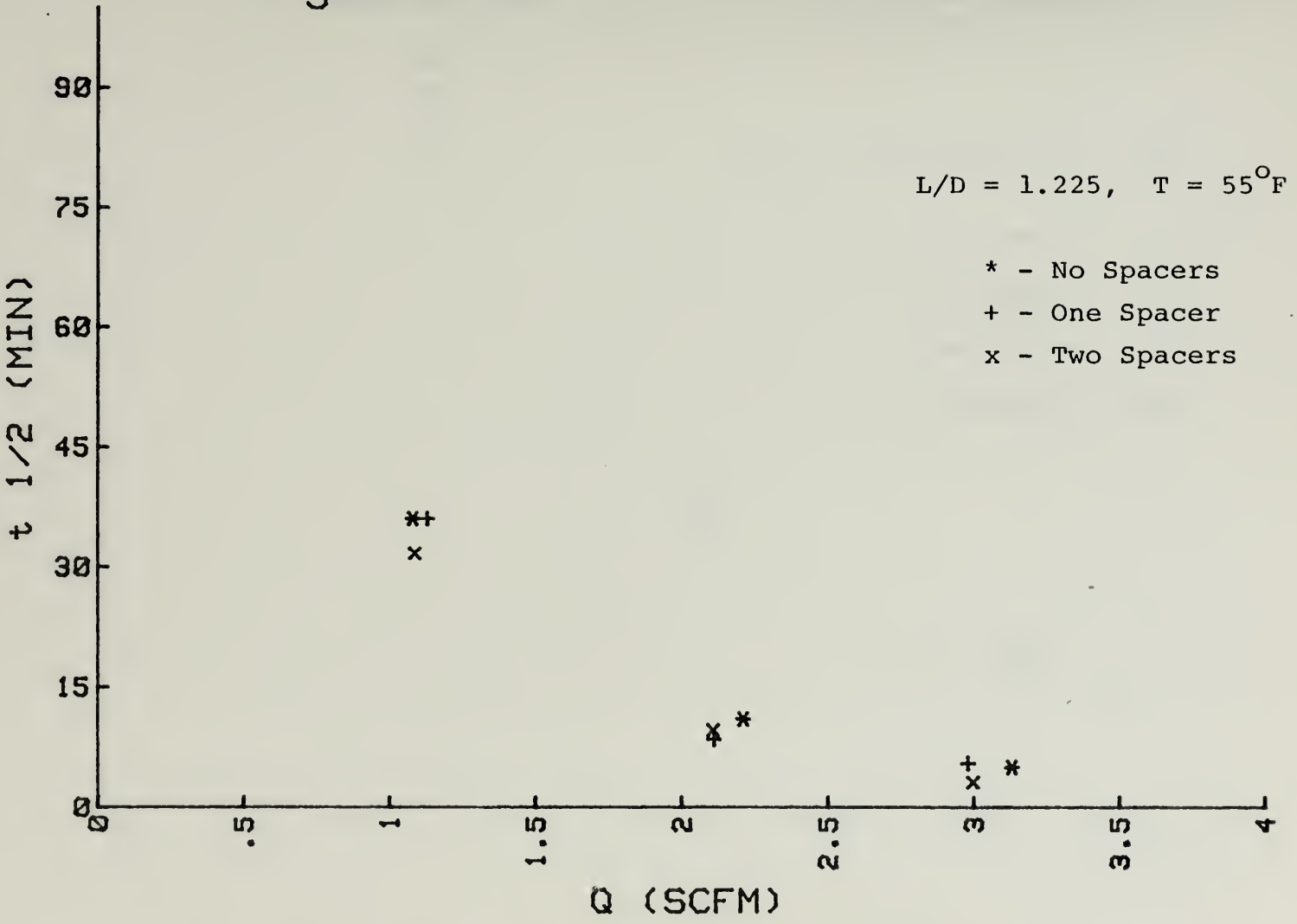
Comparison of Canisters With and Without Spacers

Figure 33 t 1/2 vs Q



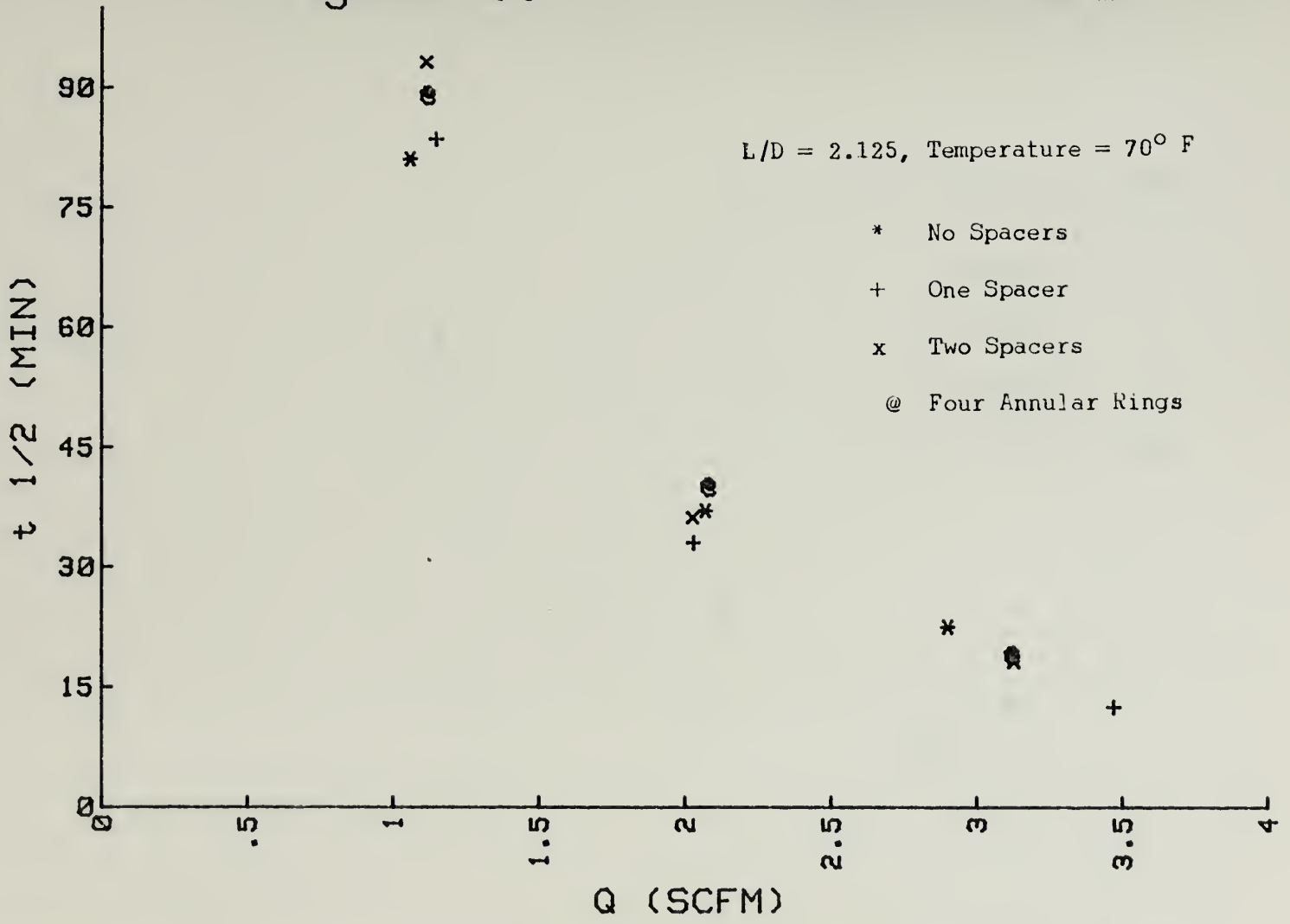
Comparison of Canisters With and Without Spacers

Figure 34 t 1/2 vs Q



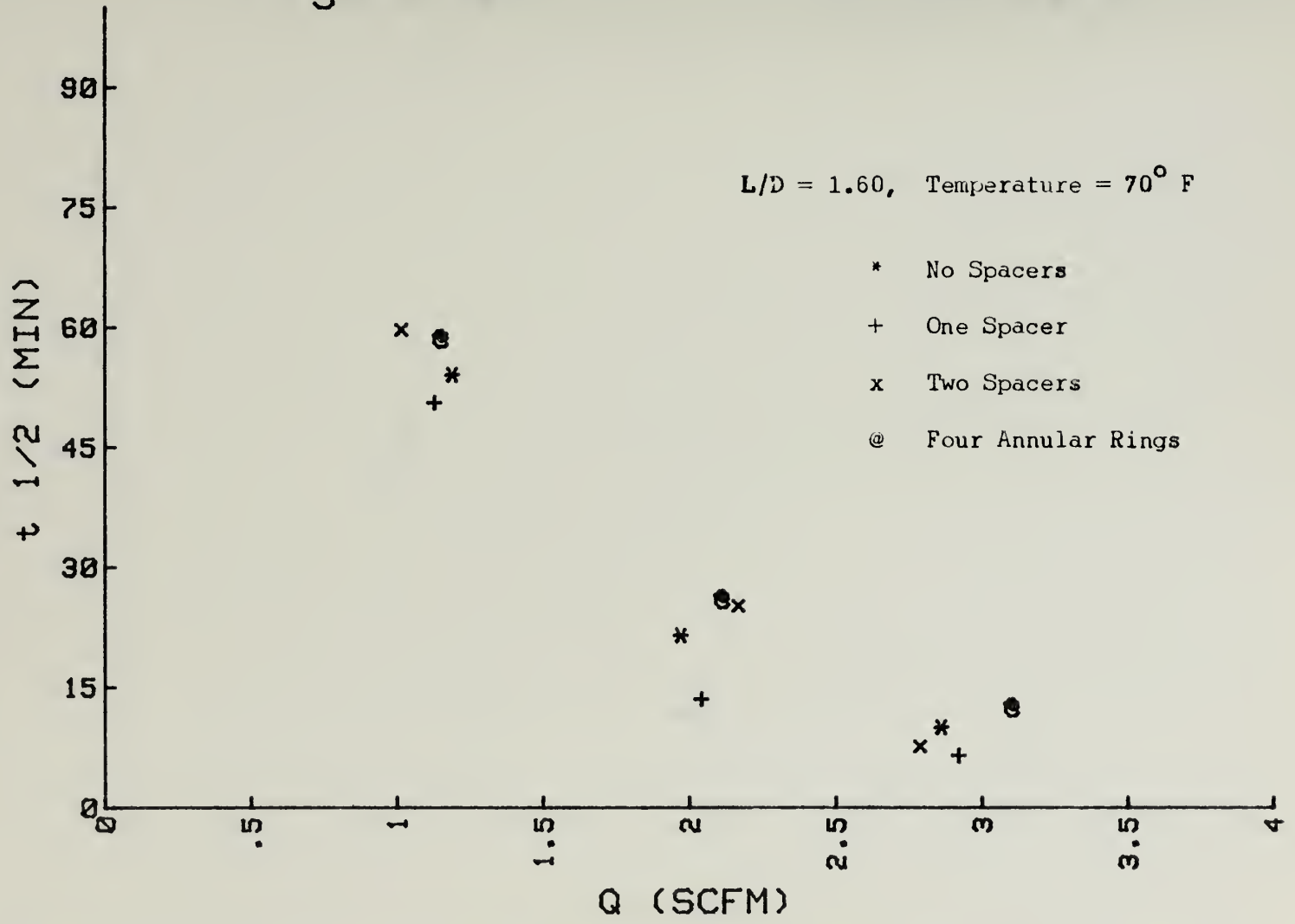
Comparison of Canisters With and Without Spacers

Figure 35 t 1/2 vs Q



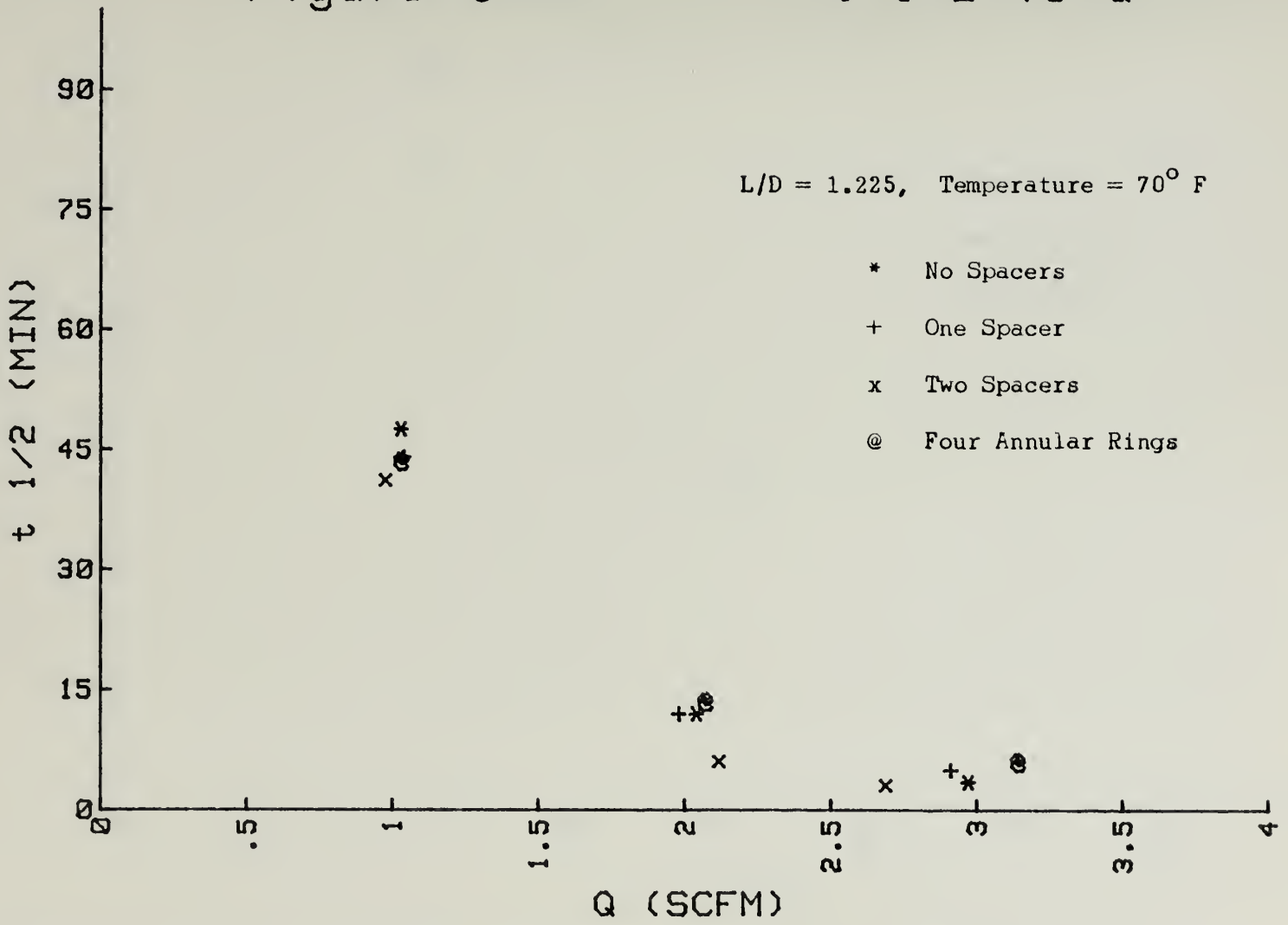
Comparison of Canisters Without Spacers to Canisters With Either Spacers or Annular Rings

Figure 36 t 1/2 vs Q



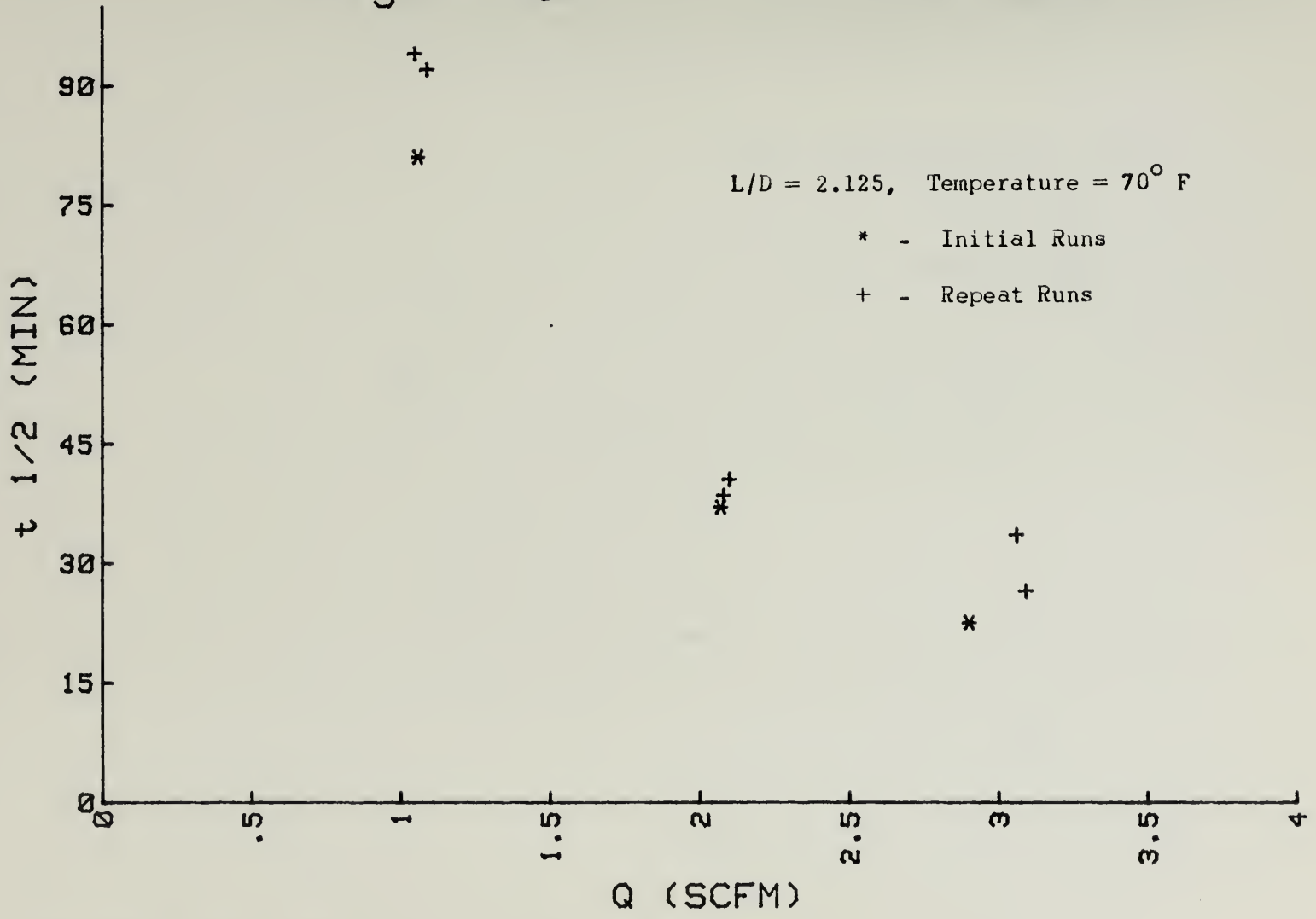
Comparison of Canisters Without Spacers to Canisters With Either Spacers or Annular Rings

Figure 37 t 1/2 vs Q



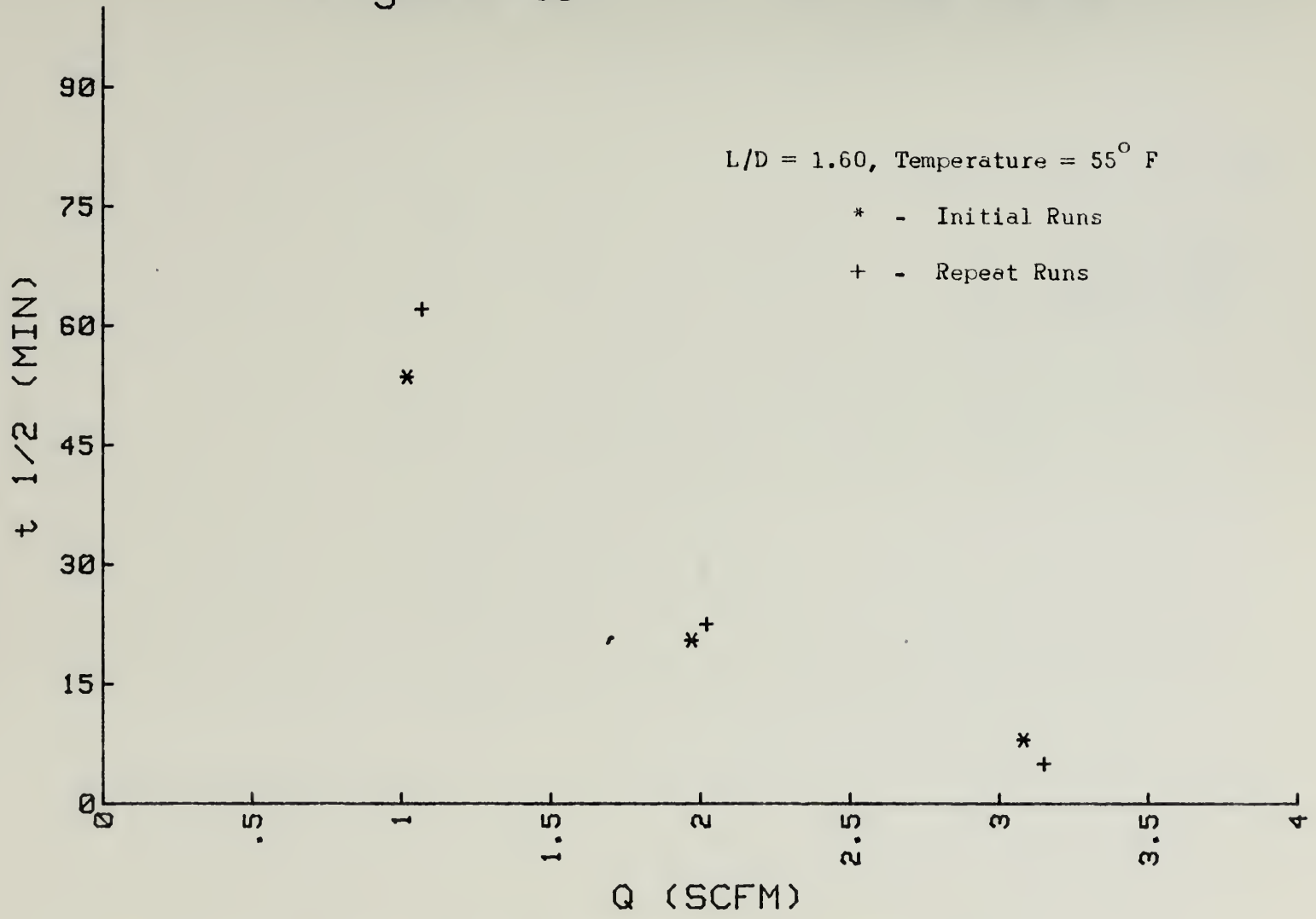
Comparison of Canisters Without Spacers to Canisters With Either Spacers or Annular Rings

Figure 38 t 1/2 vs Q



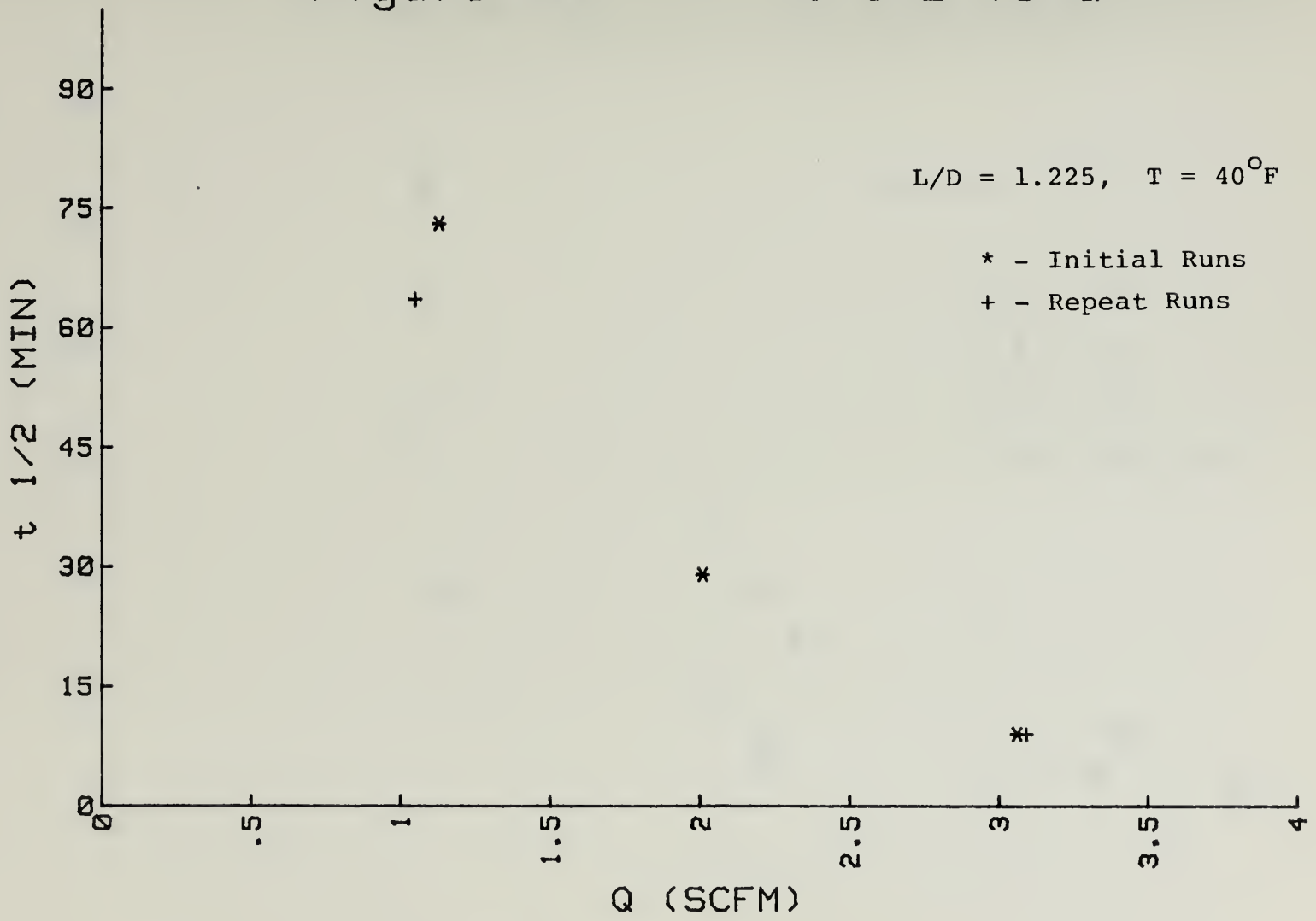
Comparison of Initial and Repeat Runs, No Spacers or Annular Rings

Figure 39 t 1/2 vs Q



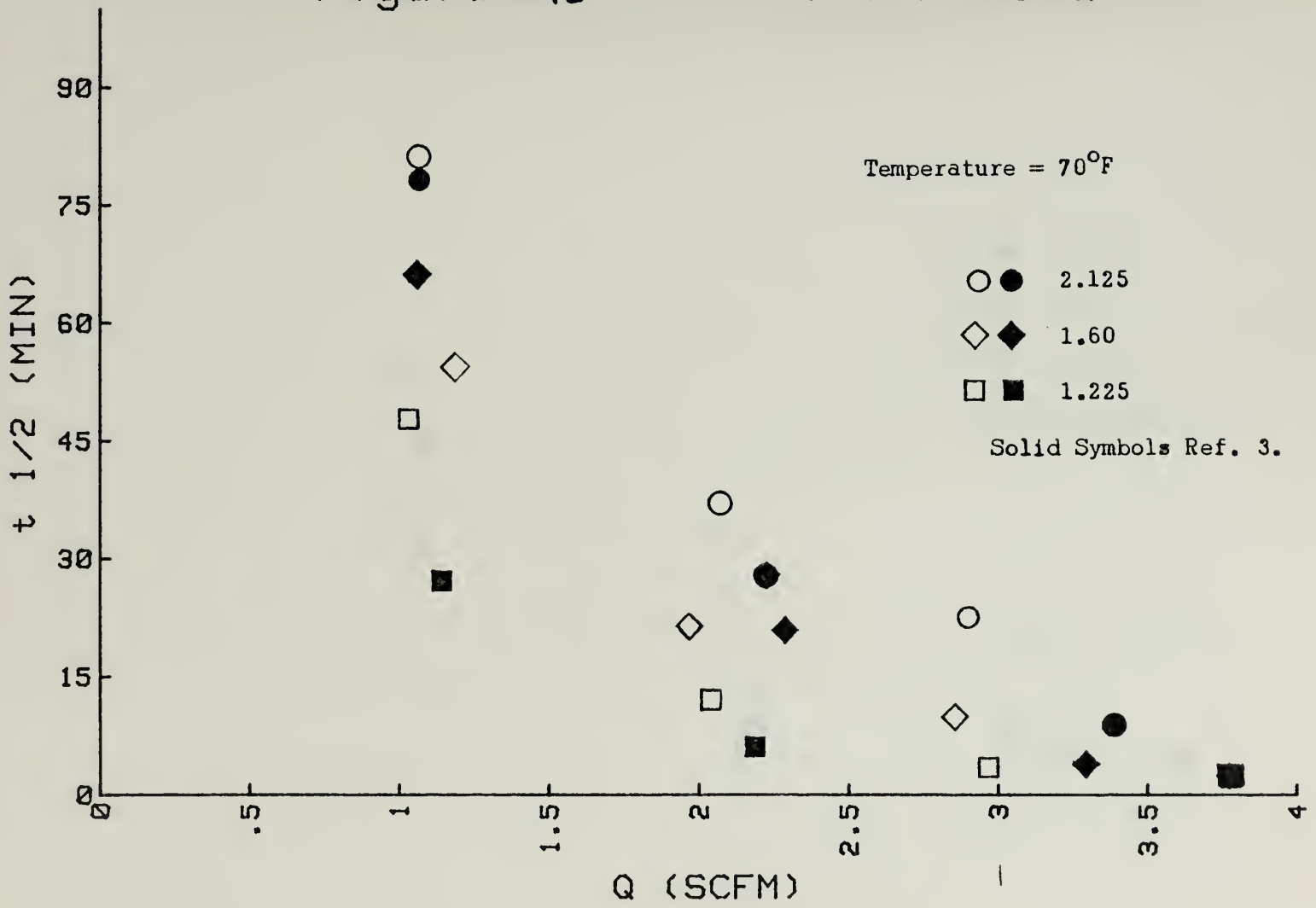
Comparison of Initial and Repeat Runs, No Spacers or Rings

Figure 40 · t 1/2 vs Q



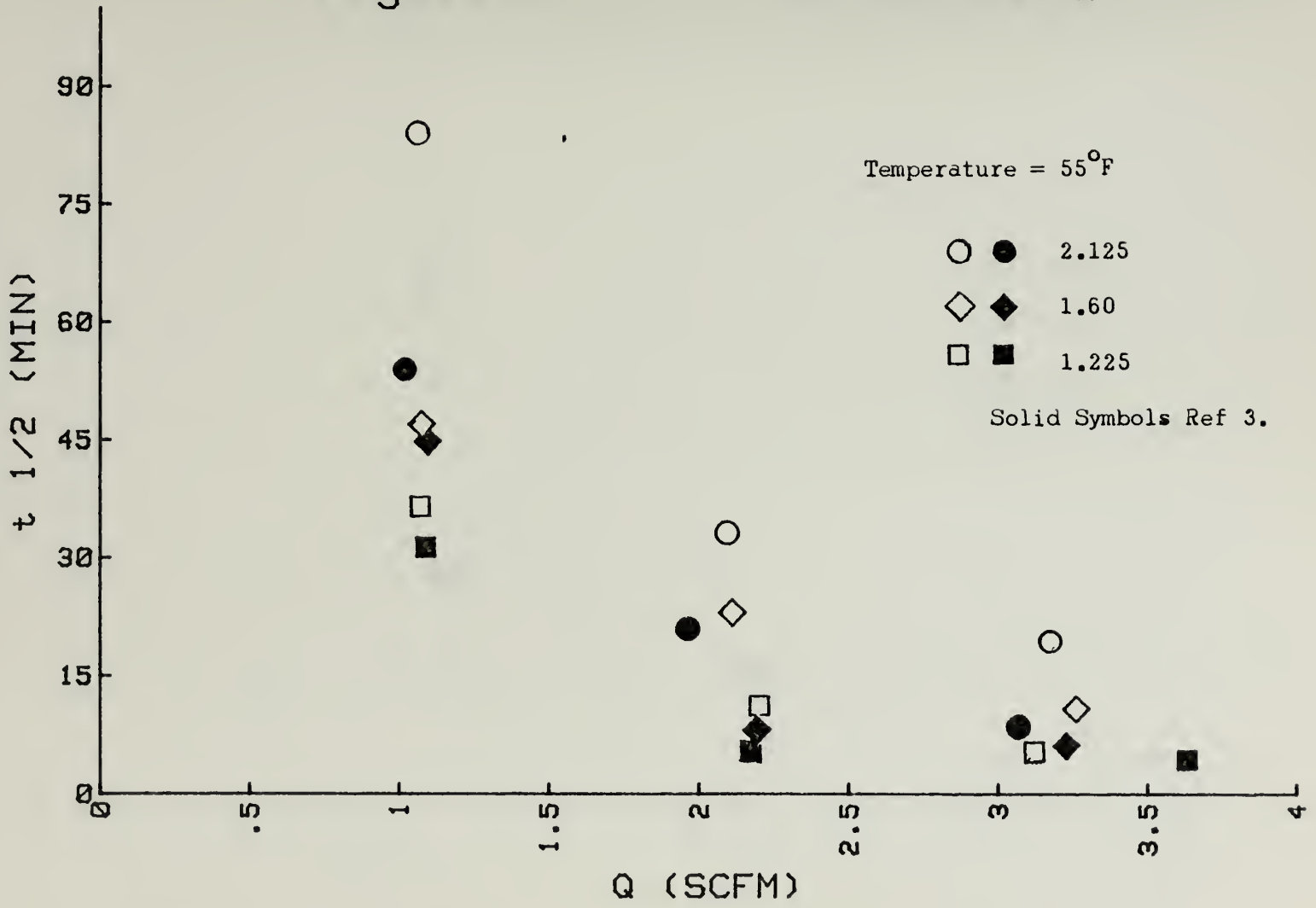
Comparison of Initial and Repeat Runs, No Spacers or Rings

Figure 41 t 1/2 vs Q



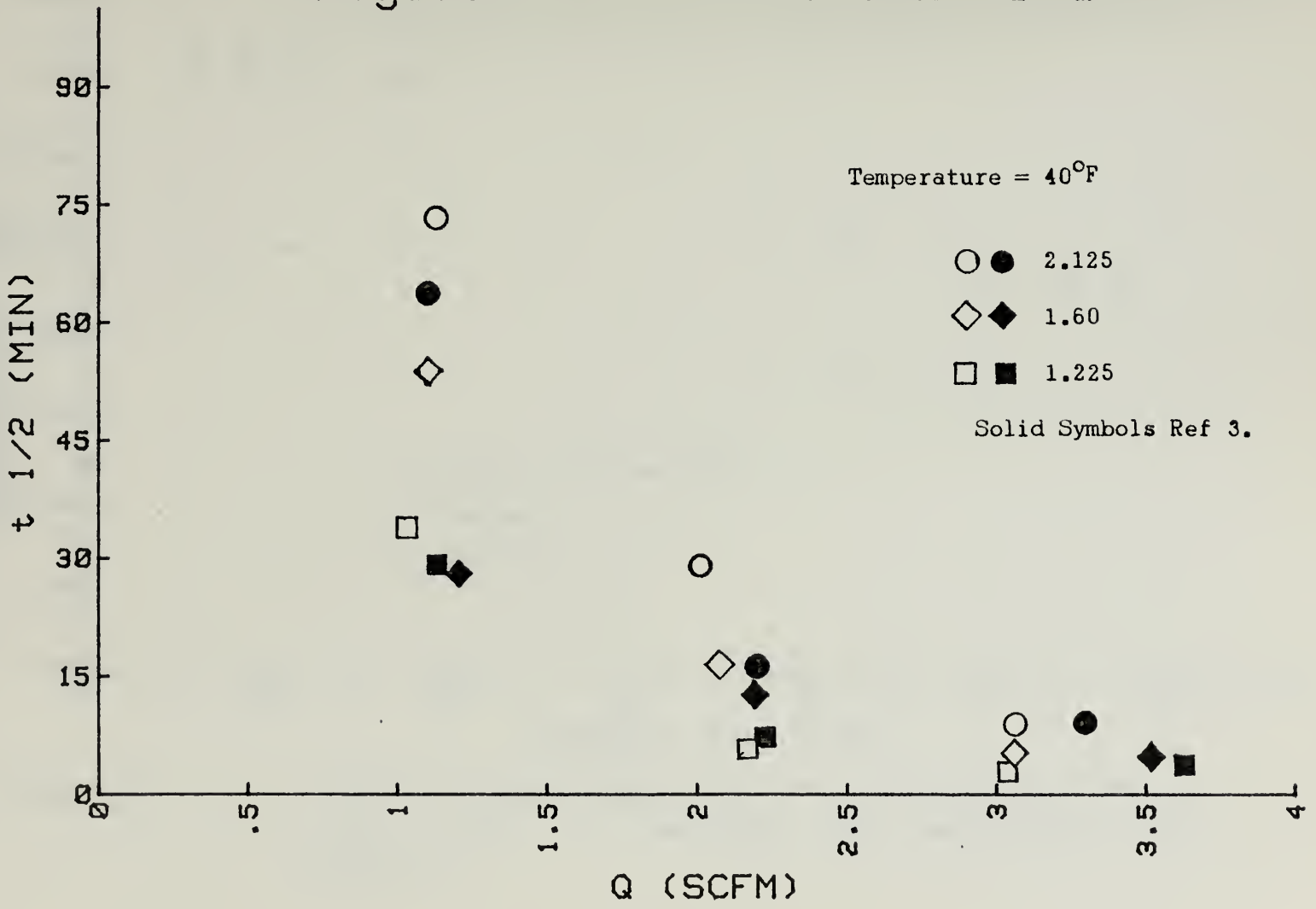
Comparison of Initial Runs with Reference [3], No Spacers or Rings

Figure 42 t 1/2 vs Q



Comparison of Initial Runs with Reference [3], No Spacers or Rings

Figure 43 t 1/2 vs Q



Comparison of Initial Runs with Reference [3], No Spacers or Rings

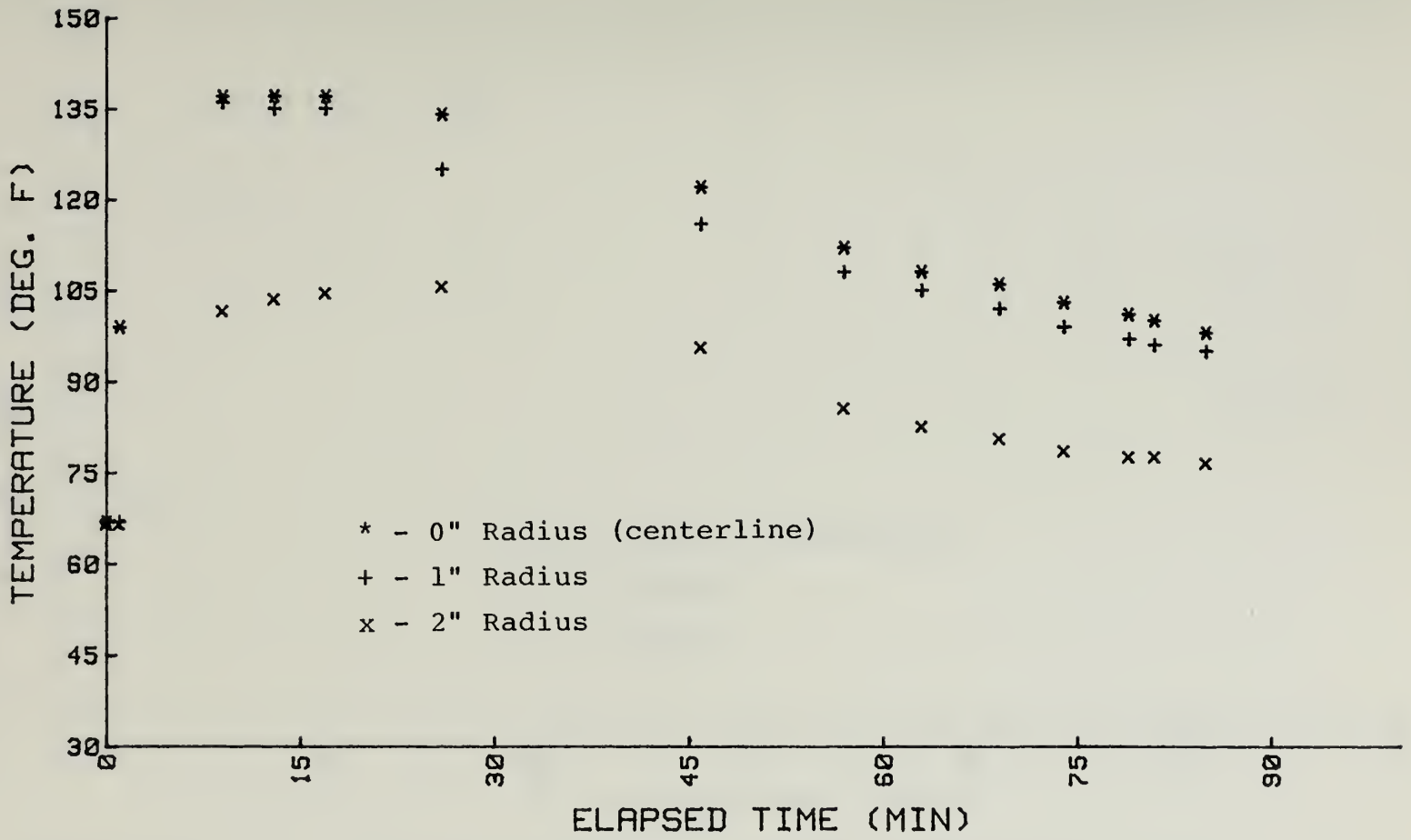


Figure 44. Canister Radial Temperature as a Function of Time. L/D = 2.125, Q = 1.06 SCFM, Bath Temperature = 70°F Station 3.

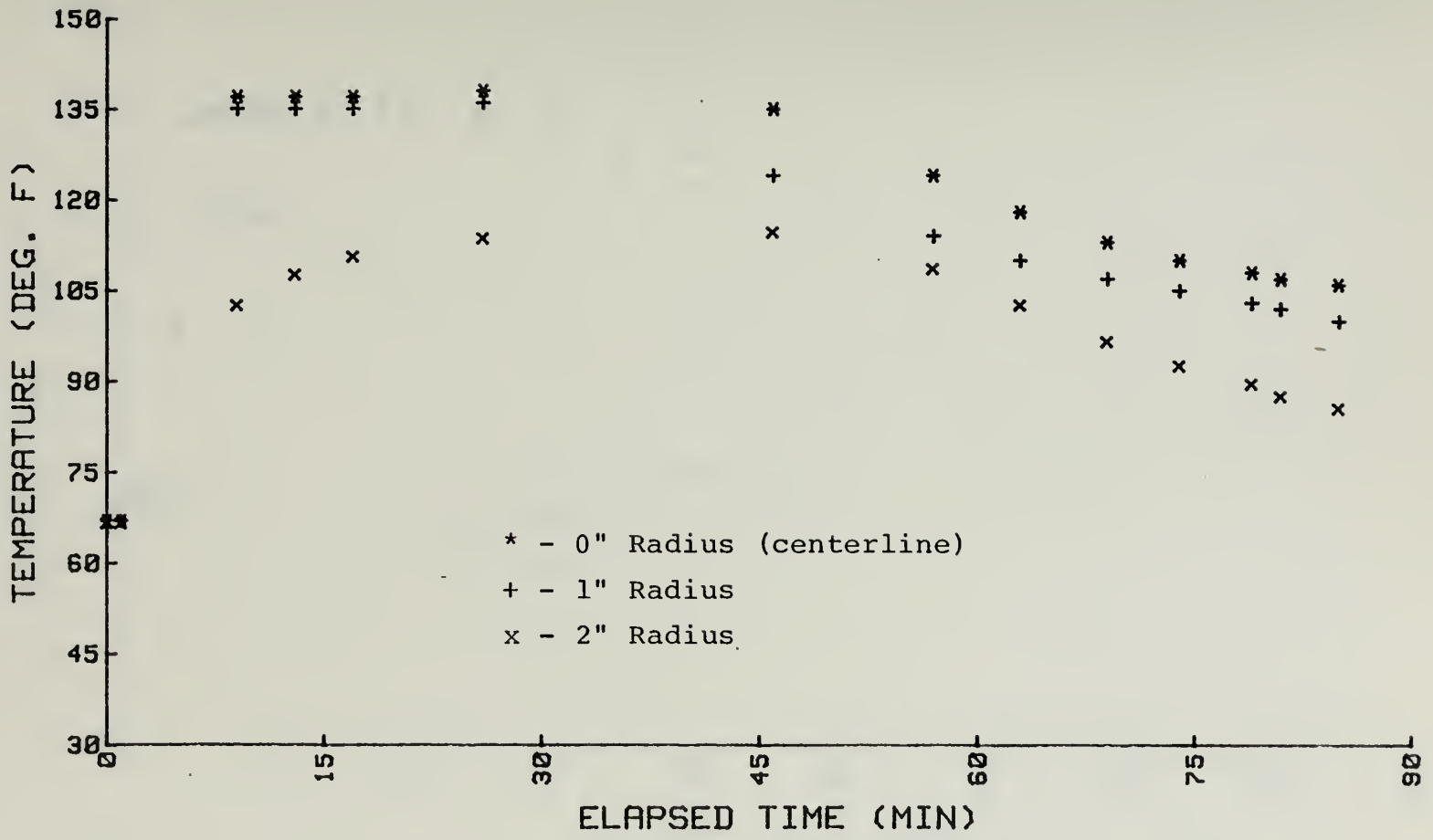


Figure 45. Canister Radial Temperature as a Function of Time, L/D = 2.125, Q = 1.06 SCFM, Bath Temperature = 70° F, Station 4.

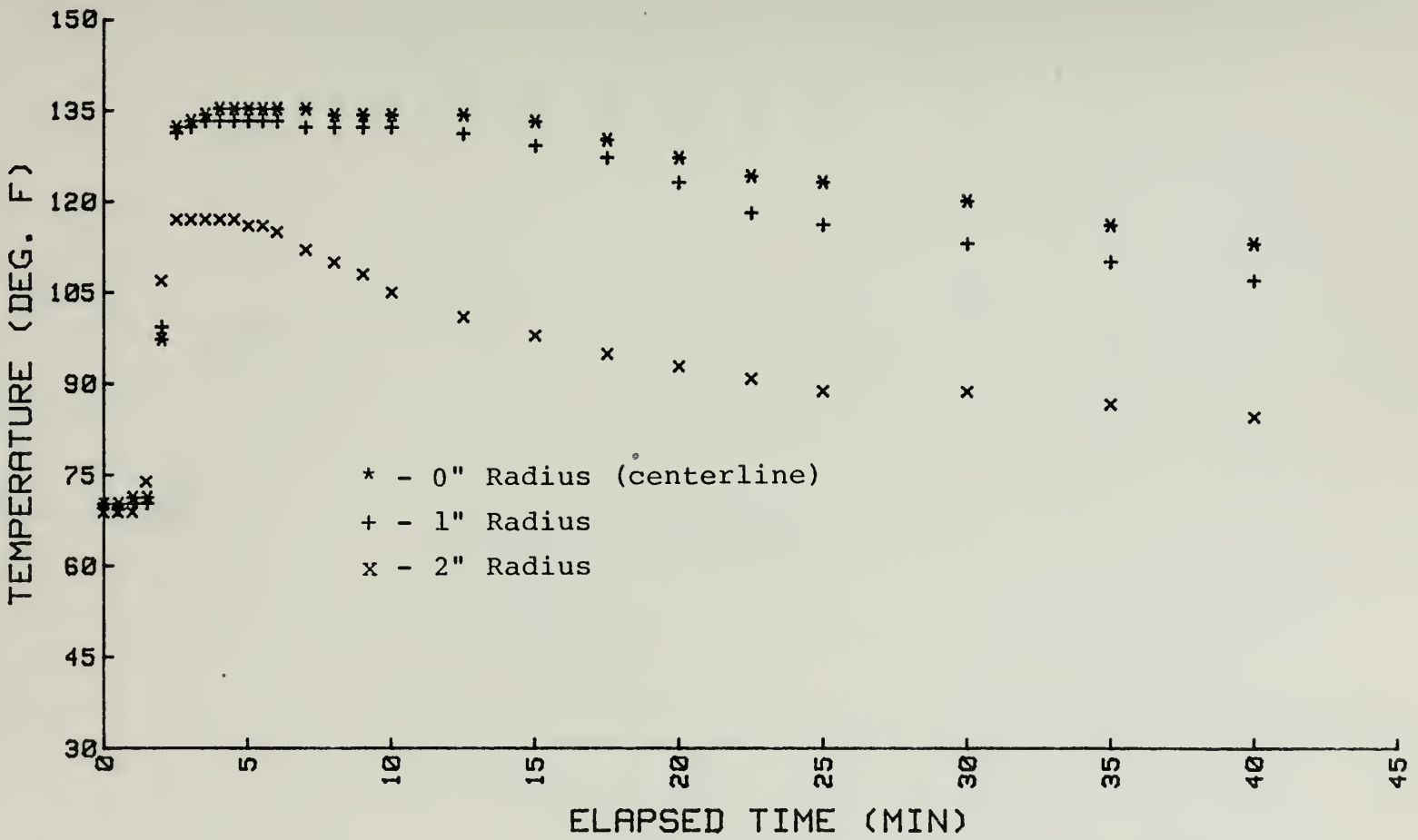


Figure 46. Canister Radial Temperature as a Function of Time. L/D = 2.125, Q = 2.10 SCFM, Bath Temperature = 70°F, Station 3.

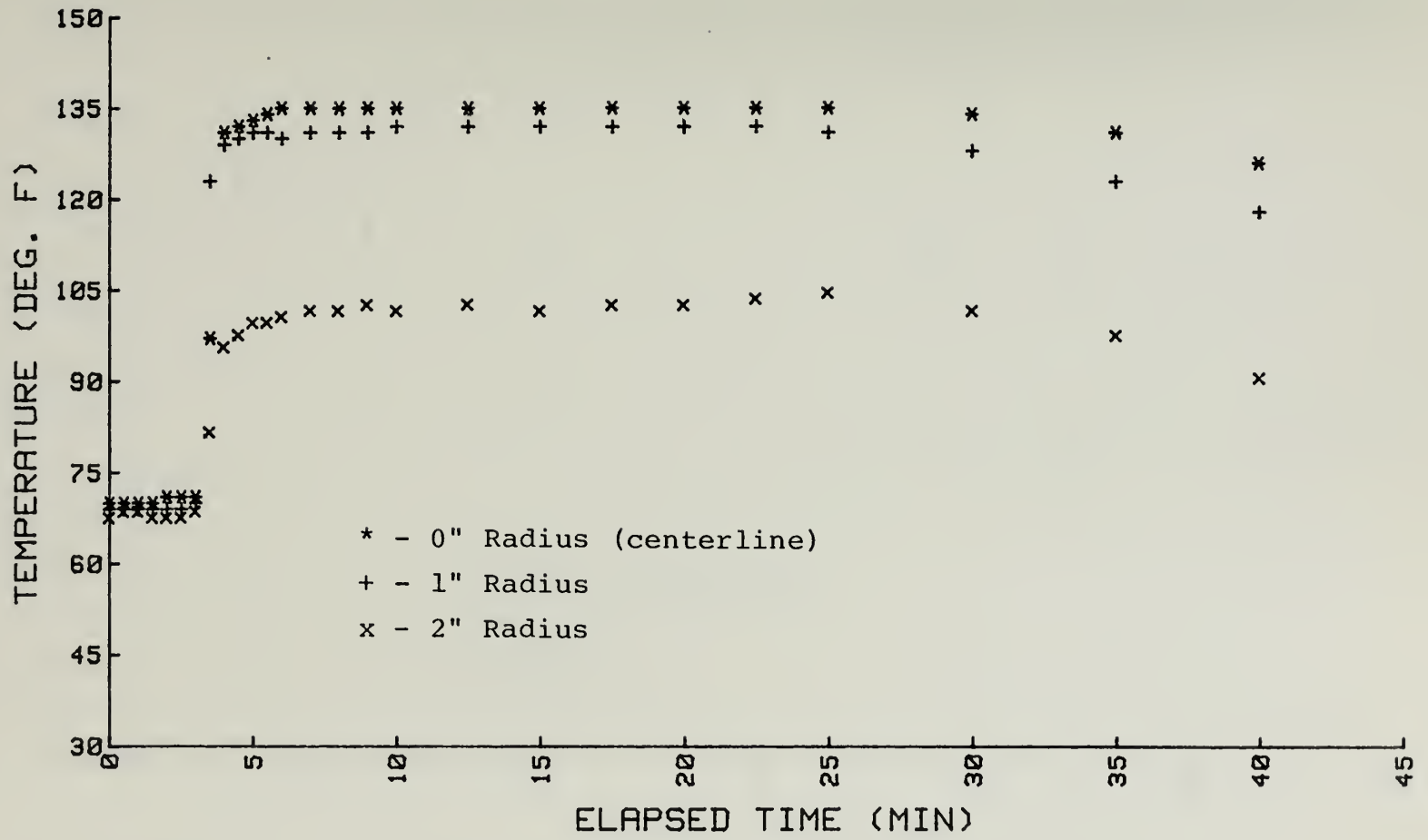


Figure 47. Canister Radial Temperature as a Function of Time. L/D = 2.125, Q = 2.10 SCFM, Bath Temperature - 70°F, Station 4.

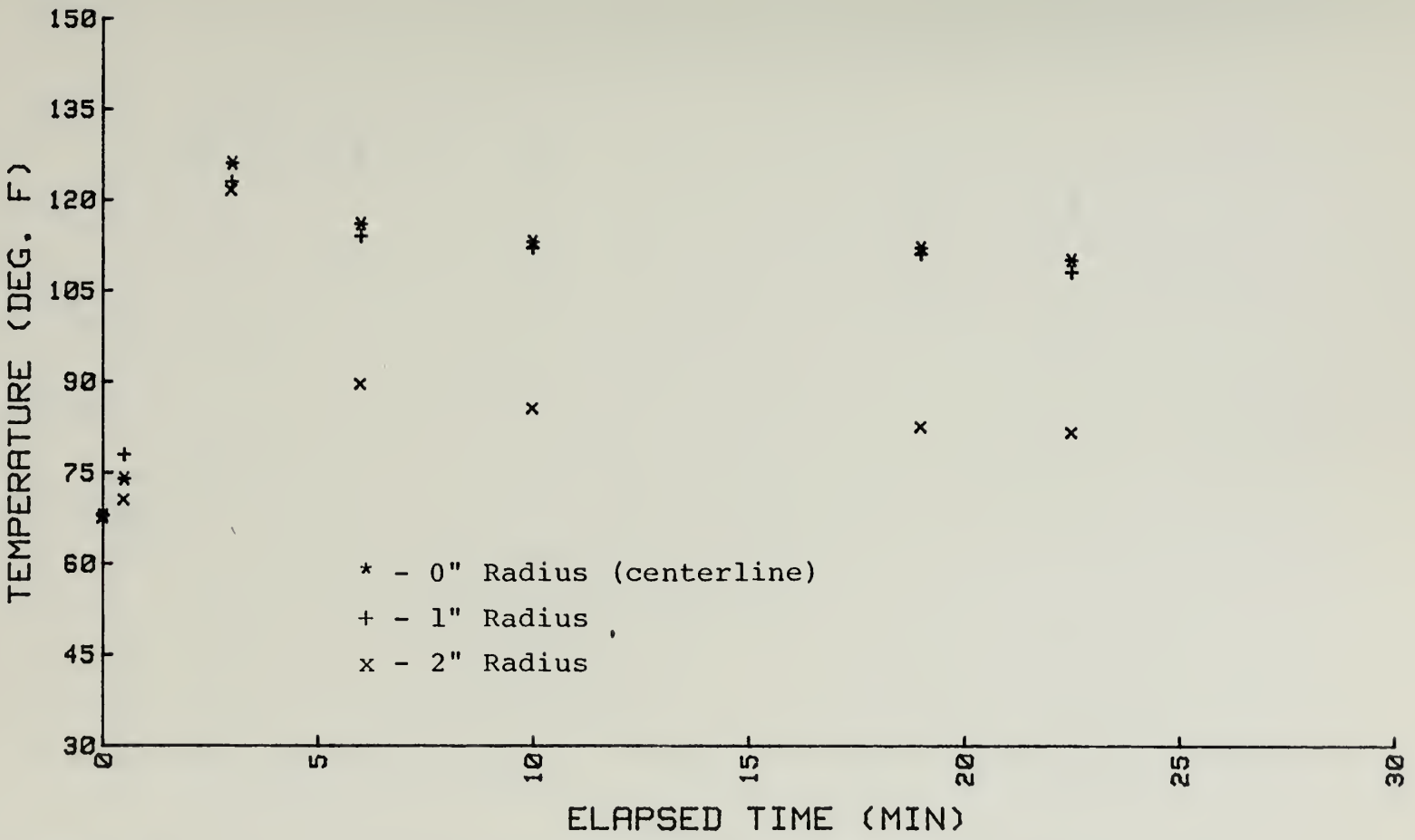


Figure 48. Canister Radial Temperature as a Function of Time. L/D = 2.125, Q= 2.90 SCFM, Bath Temperature = 70°F, Station 3.

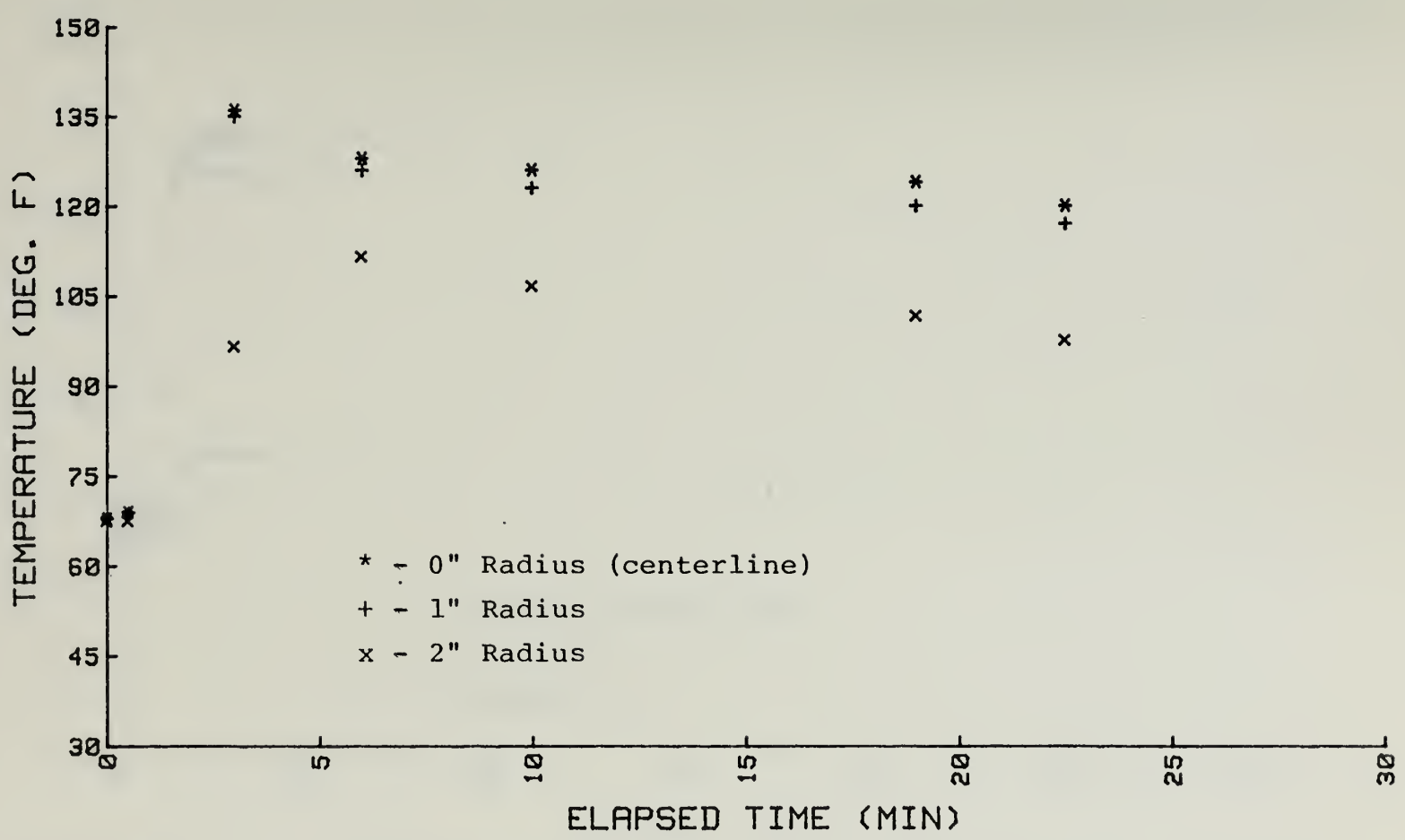


Figure 49. Canister Radial Temperature as a Function of Time L/D = 2.125, Q = 2.90 SCFM, Bath Temperature 70°F, Station 4.

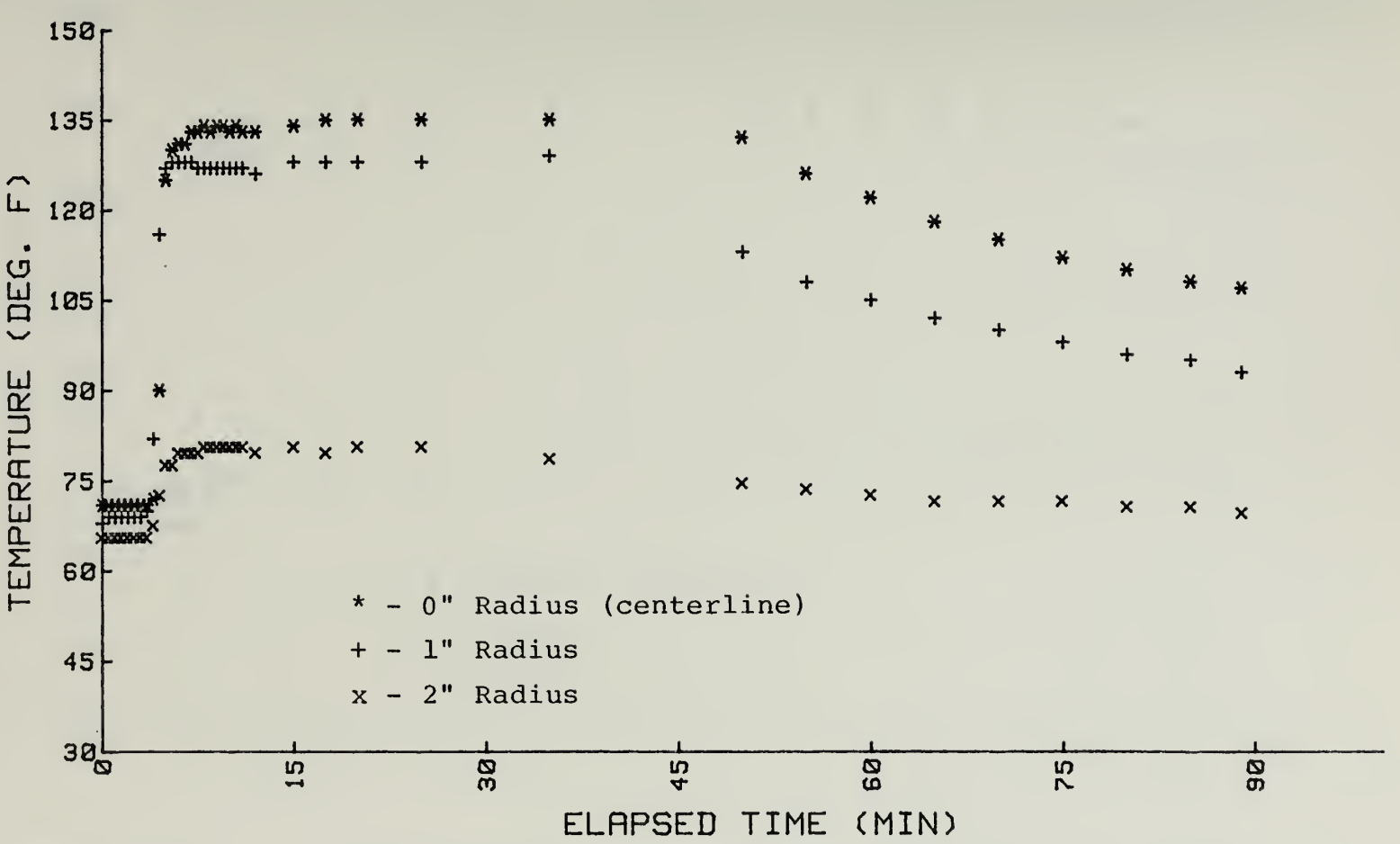


Figure 50. Annular Ring Canister Radial Temperature as a Function of Time, L/D = 2.125, Q = 1.12 SCFM, Bath Temperature = 70°F, Station 3.

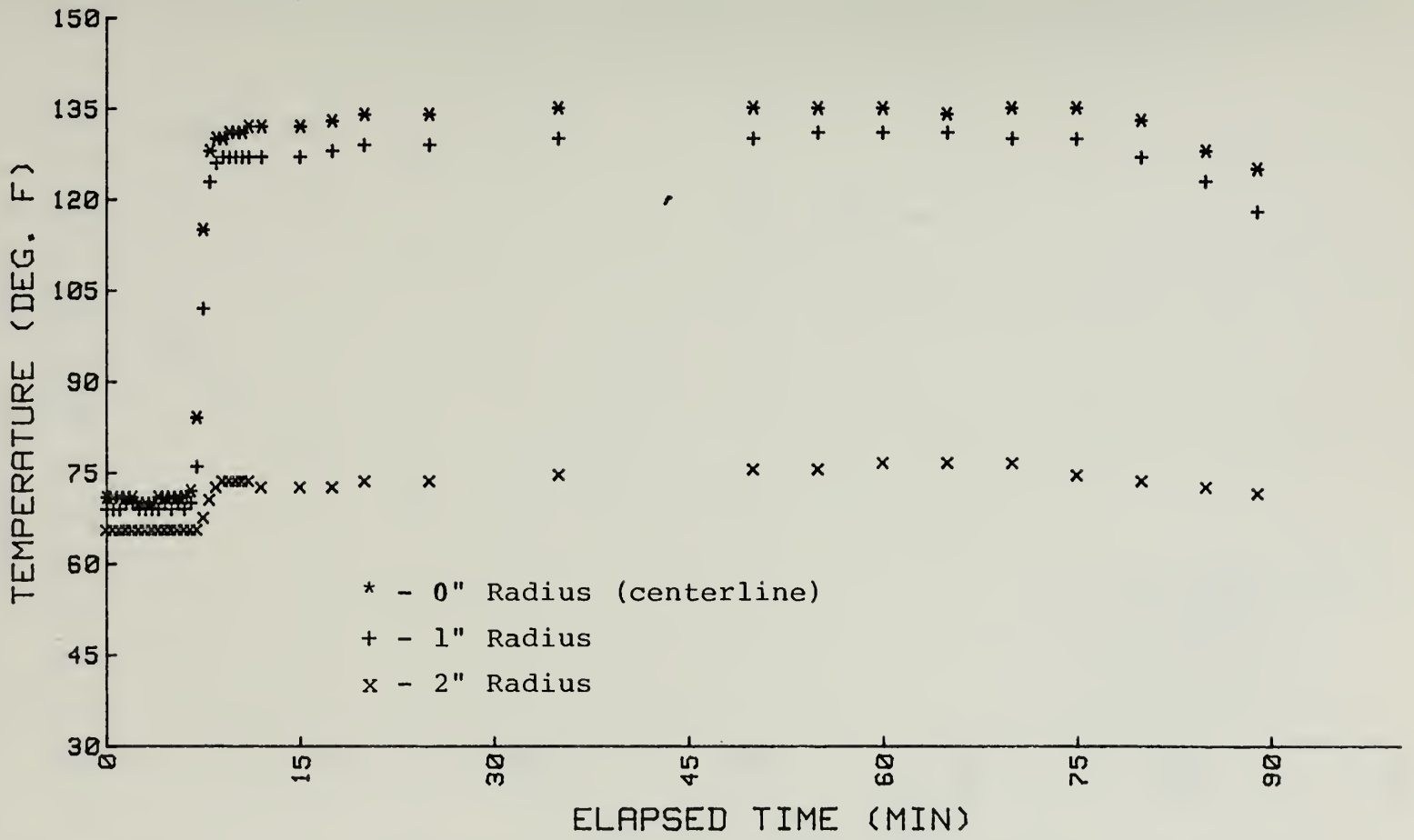


Figure 51. Annular Ring Canister Radial Temperature as a Function of Time, L/D = 2.125, Q = 1.12 SCFM, Bath Temperature = 70°F Station 4.

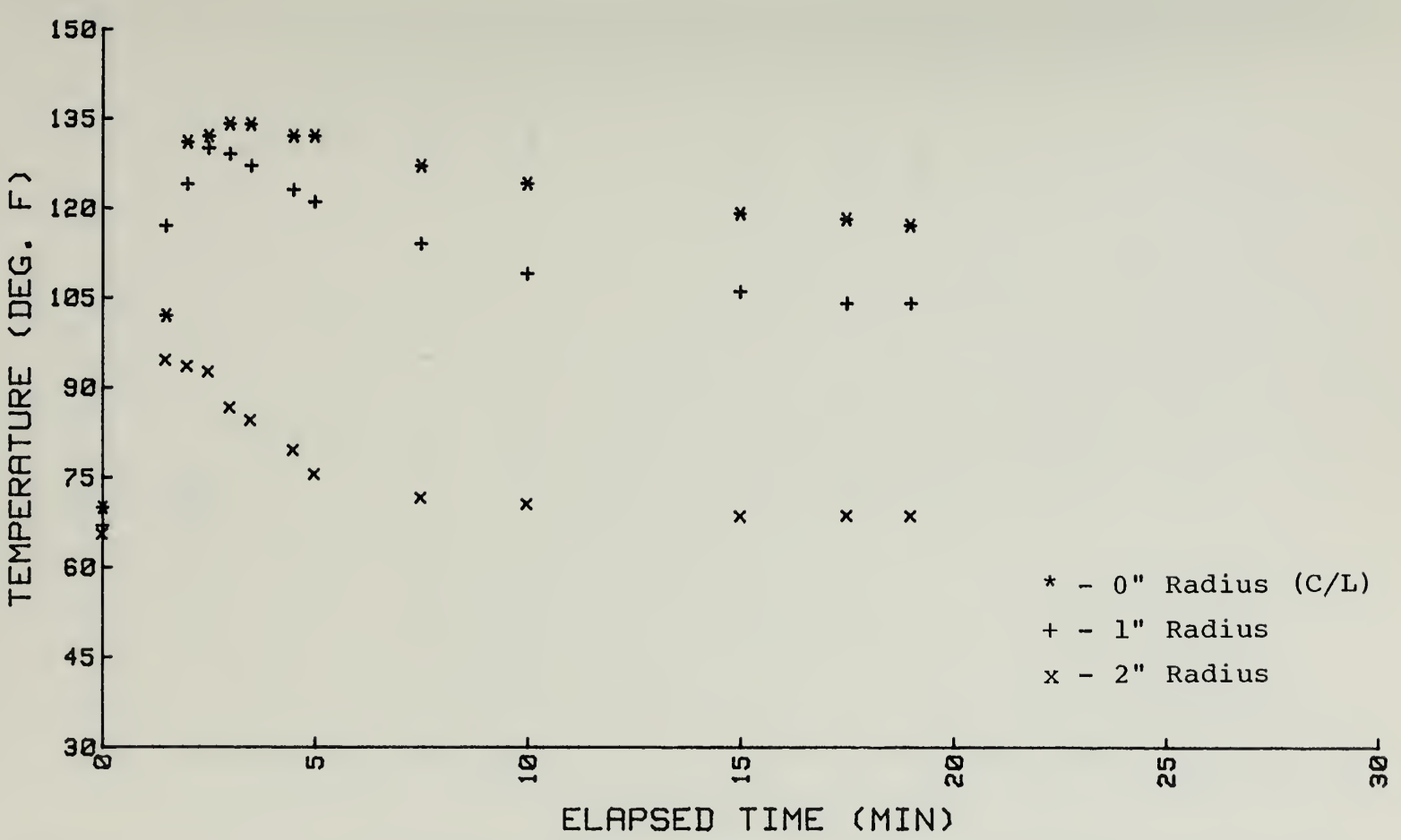


Figure 52. Annular Ring Canister Radial Temperature as a Function of Time, L/D = 2.125, Q = 3.12 SCFM, Bath Temperature = 70°F, Station 3.

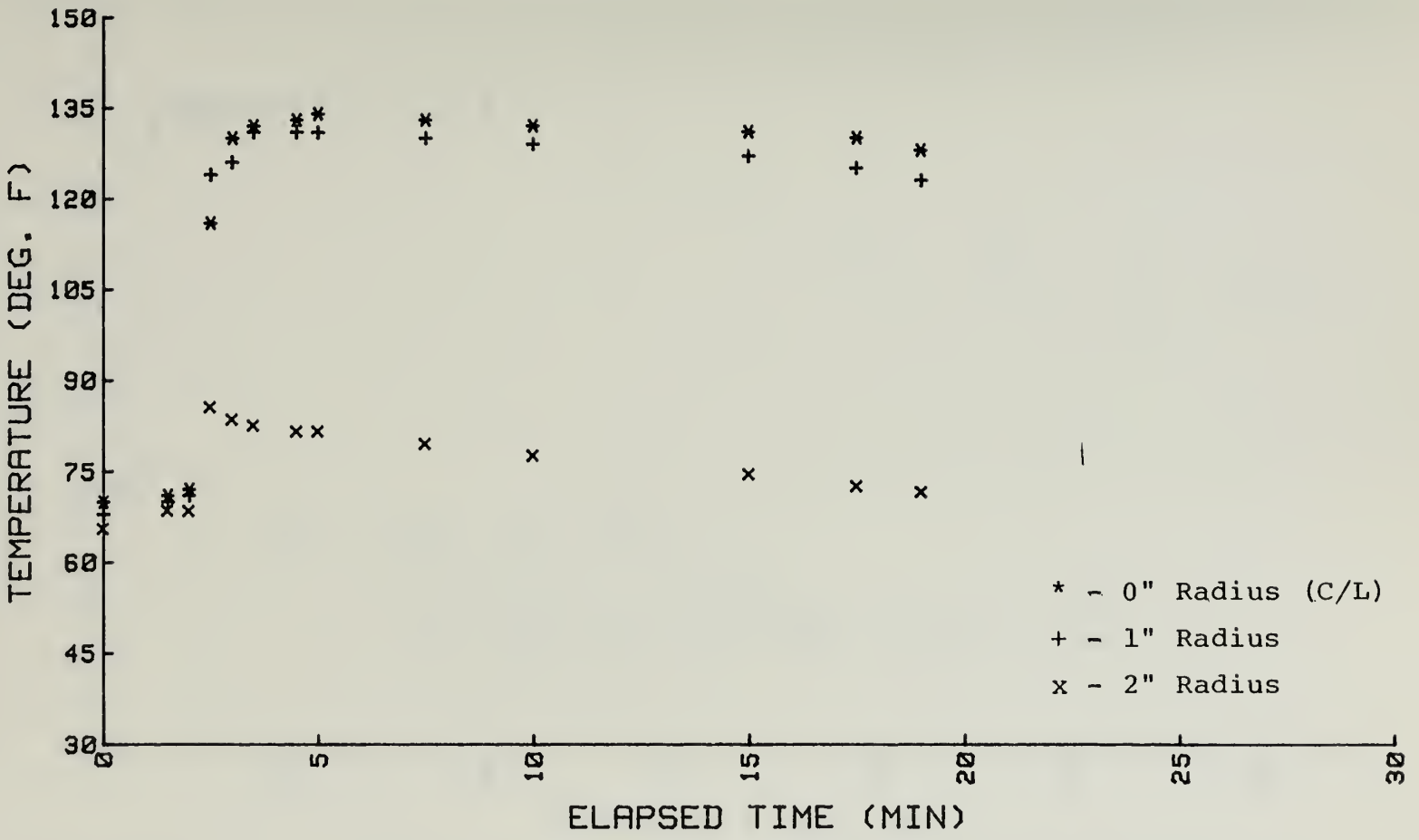


Figure 53. Annular Ring Canister Radial Temperature as a Function of Time, L/D = 2.125, Q = 3.12 SCFM, Bath Temperature = 70°F, Station 4.

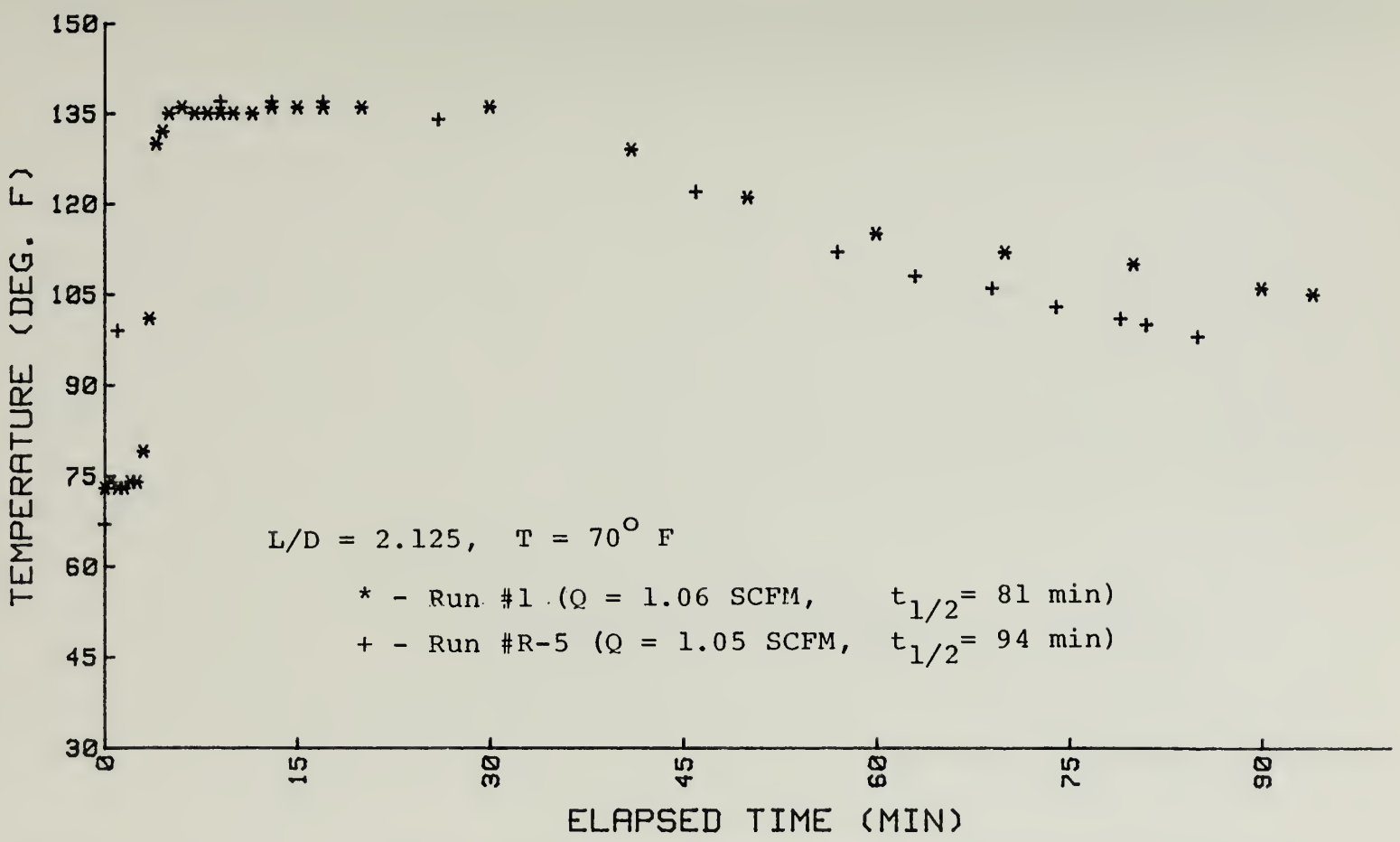


Figure 54. Comparison of Radial Temperatures of Similar L/D Runs, Station 3, 0" Radius (centerline).

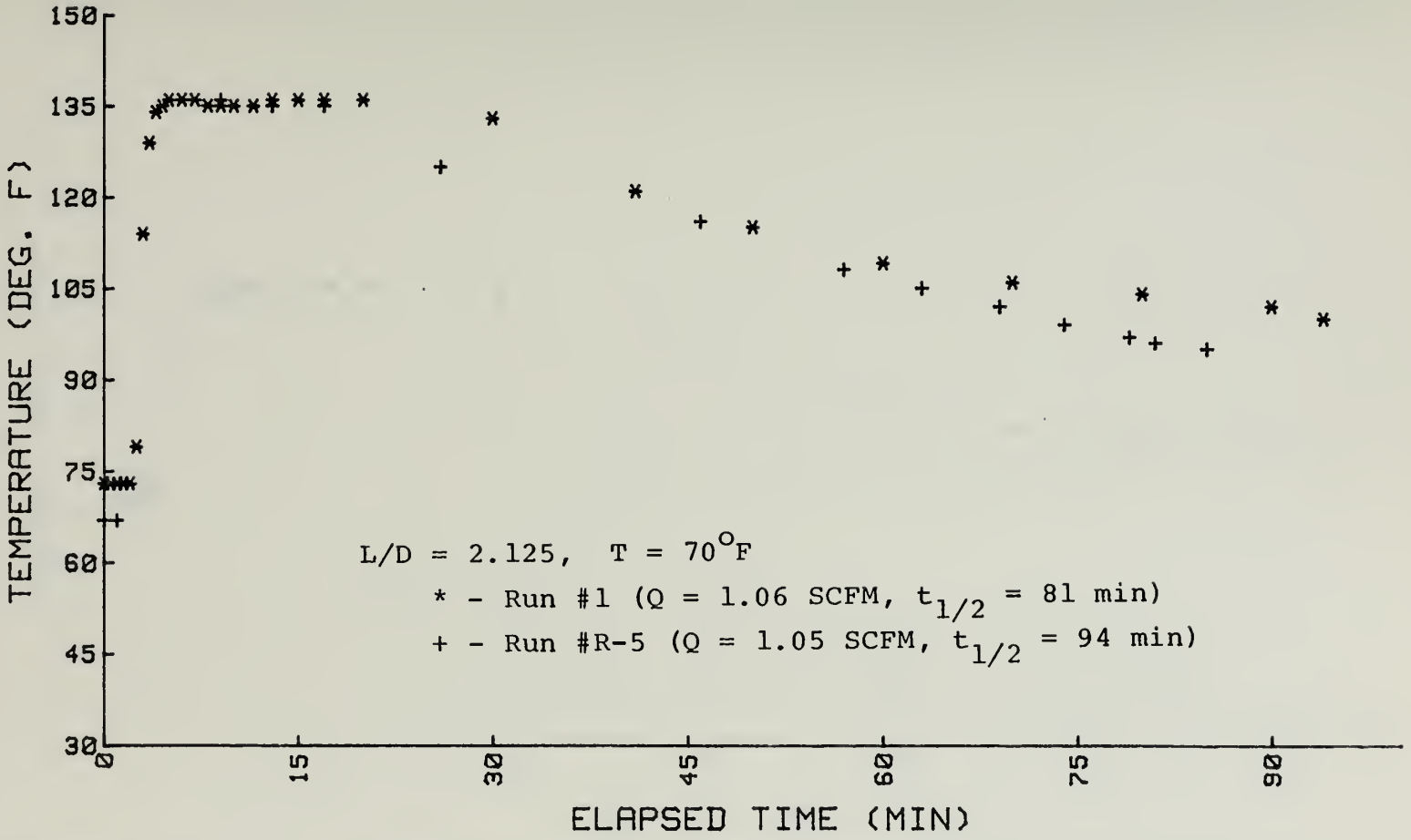


Figure 55. Comparison of Radial Temperatures of Similar L/D Runs, Station 3, 1" Radius.

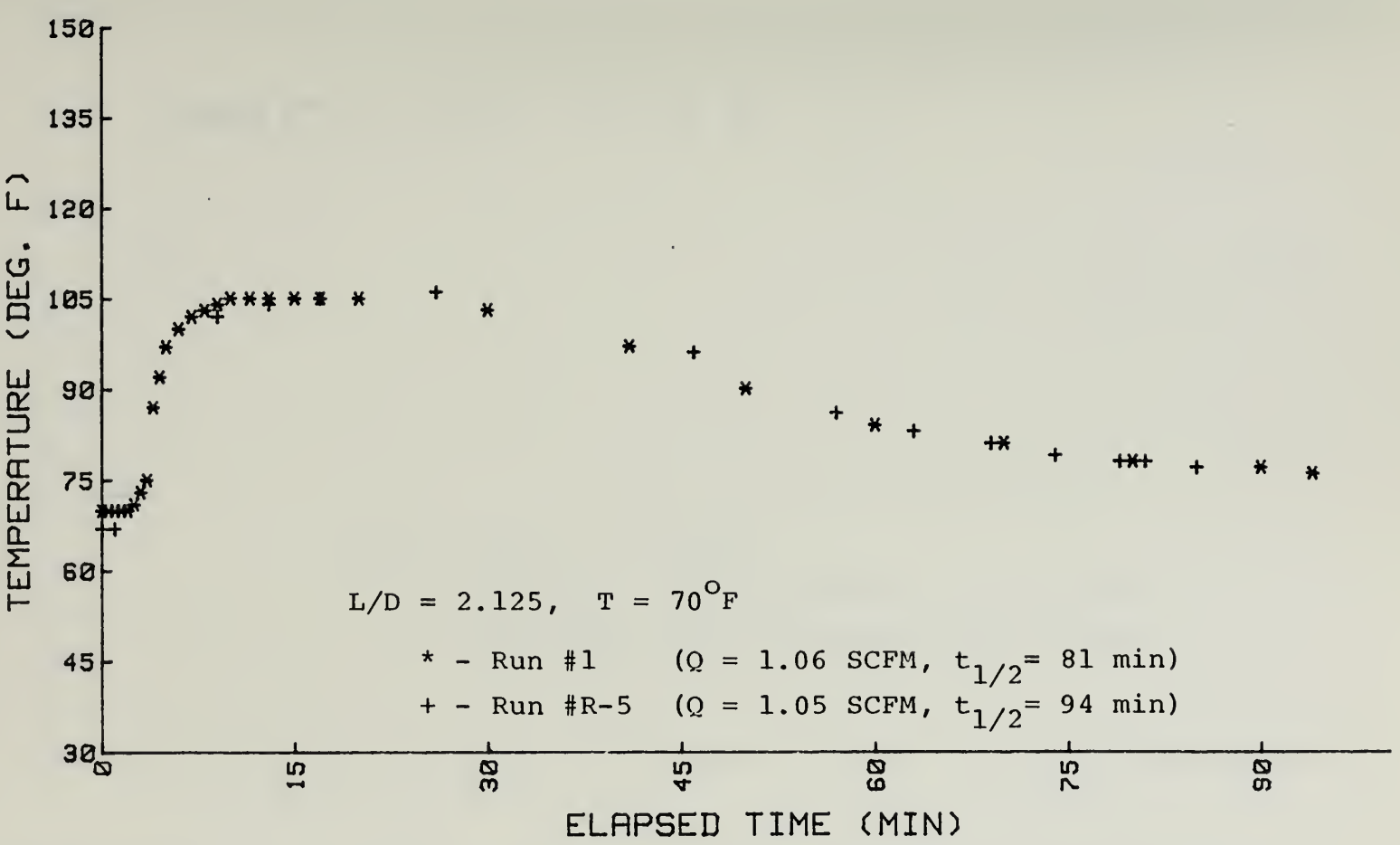


Figure 56. Comparison of Radial Temperatures of Similar L/D Runs, Station 3, 2" Radius.

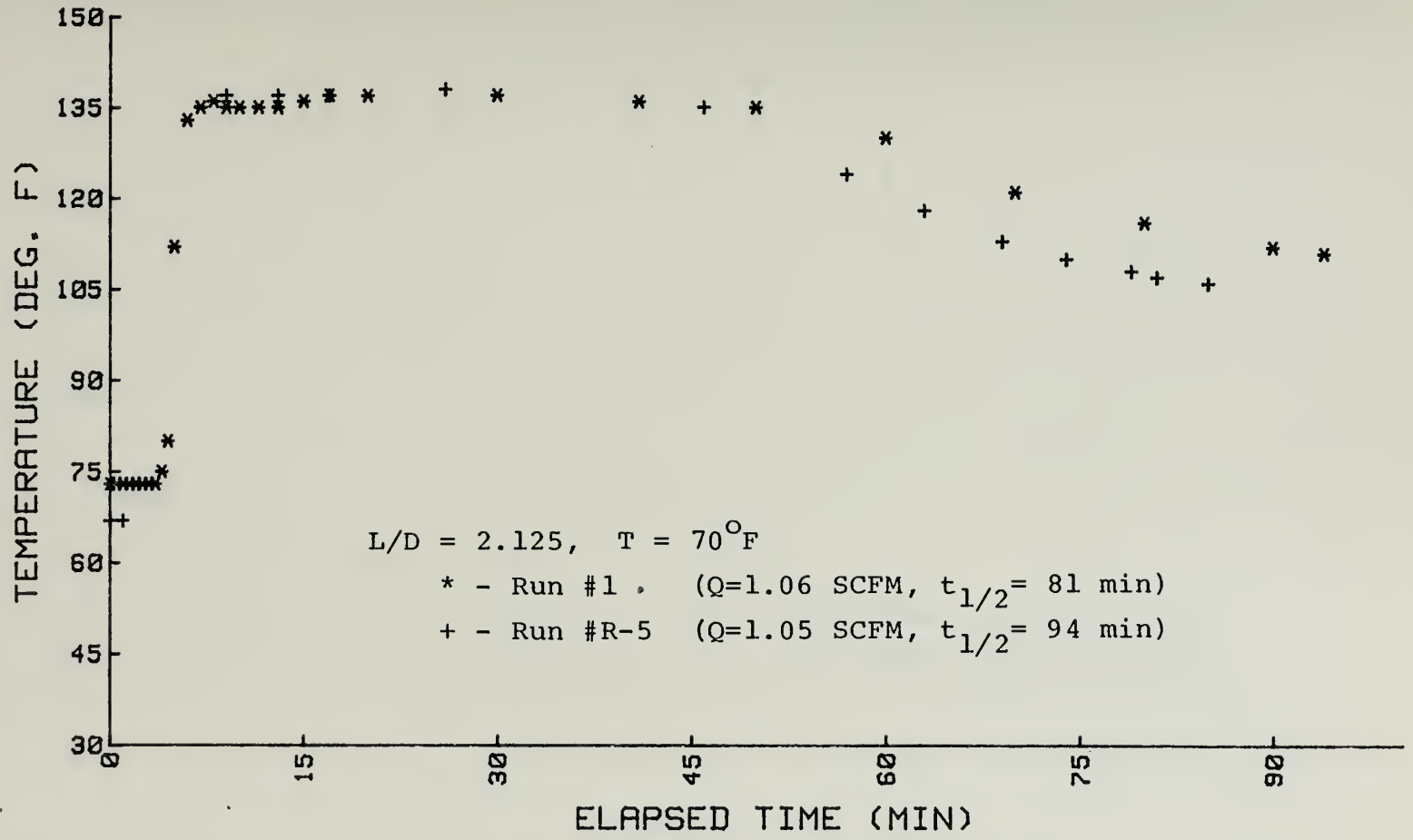


Figure 57. Comparison of Radial Temperatures of Similar L/D Runs, Station 4, 0" Radius (centerline).

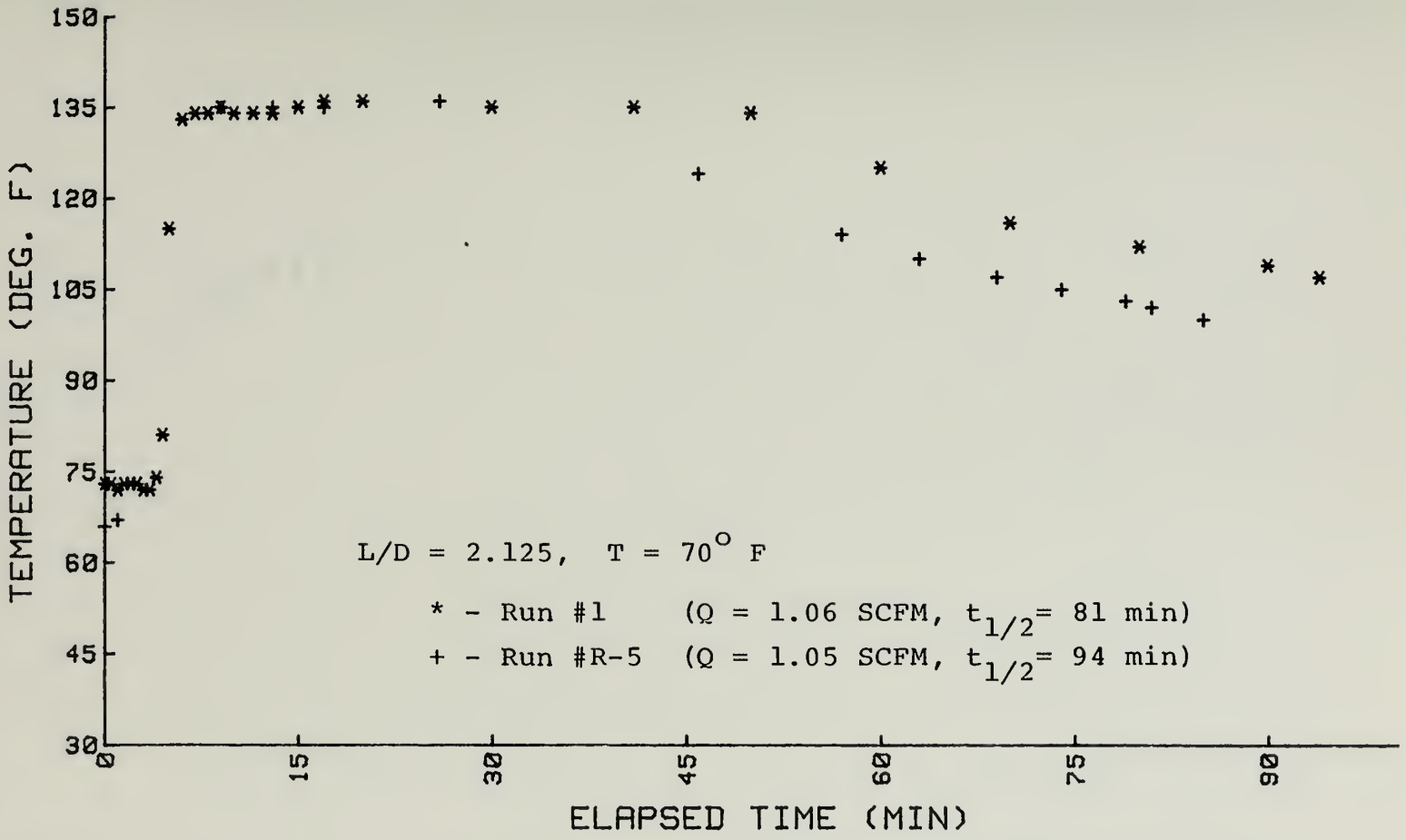


Figure 58. Comparison of Radial Temperatures of Similar L/D Runs, Station 4, 1" Radius.

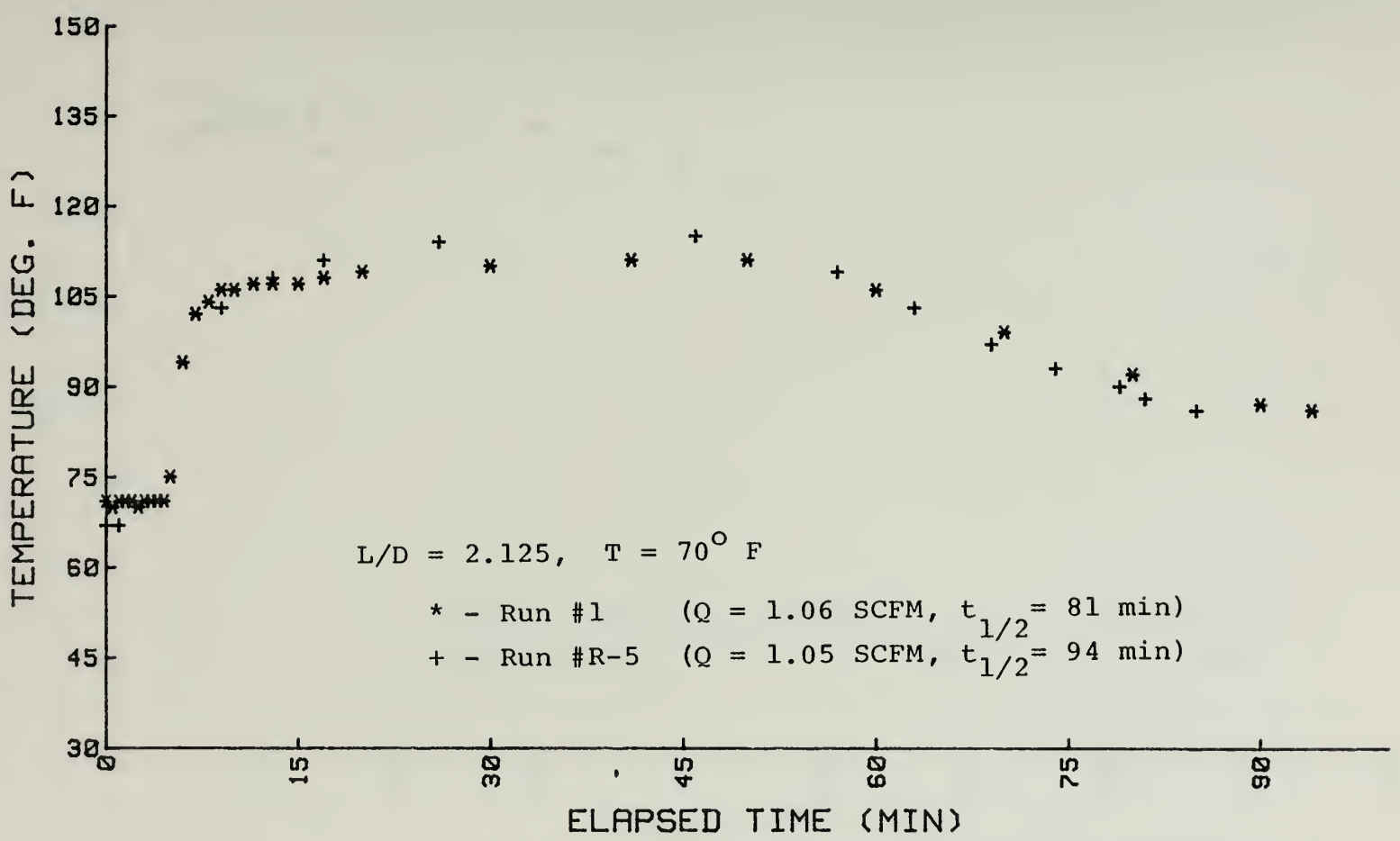


Figure 59. Comparison of Radial Temperatures of Similar L/D Runs, Station 4, 2" Radius.

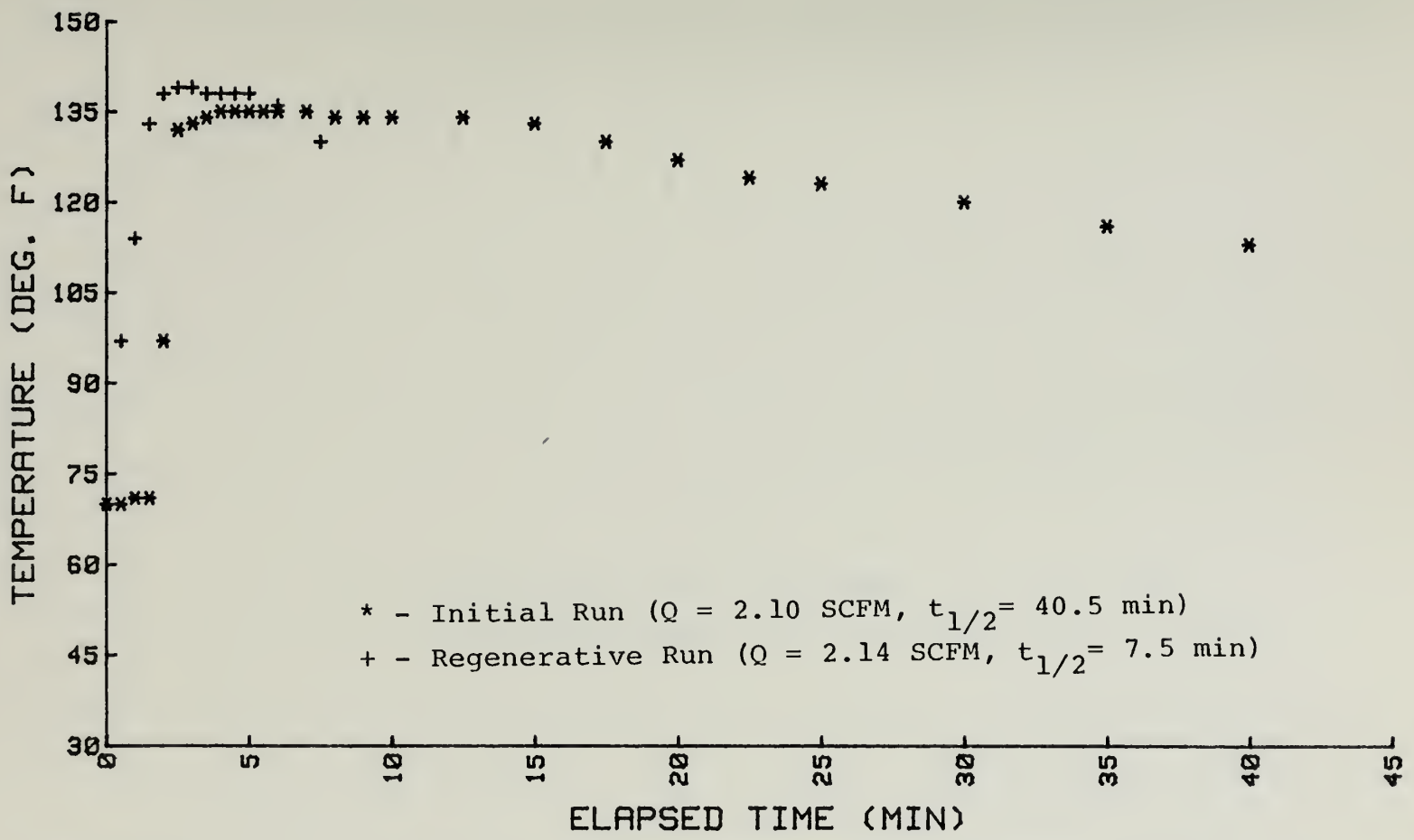


Figure 60. Comparison of Radial Temperatures between Initial and Regenerative Runs, L/D = 2.125, T = 70°F, Station 3, 0" Radius (centerline).

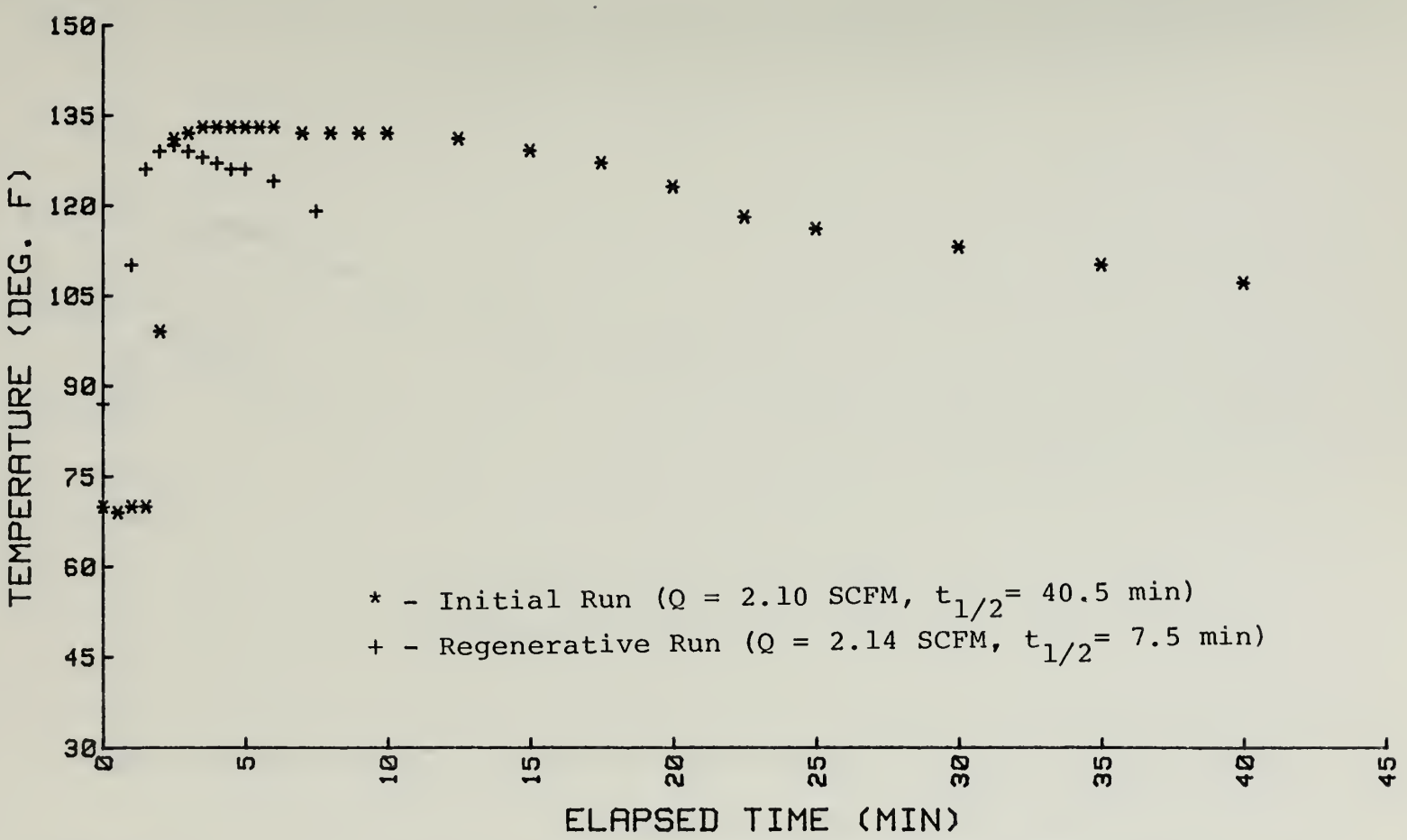


Figure 61. Comparison of Radial Temperatures between Initial and Regenerative Runs, L/D = 2.125, T = 70°F, Station 3, 1" Radius.

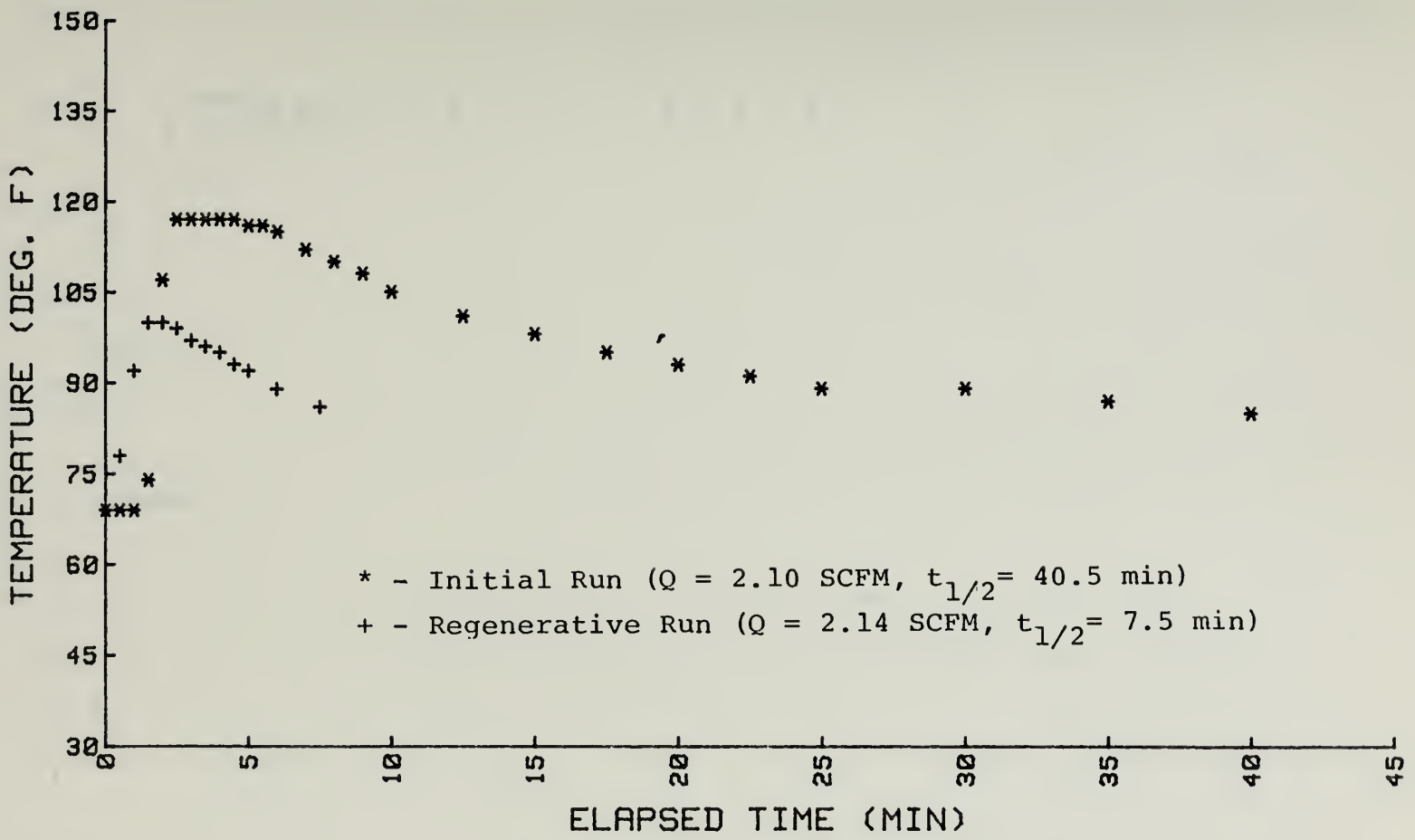


Figure 62. Comparison of Radial Temperatures between Initial and Regenerative Runs, L/D = 2.125, T = 70°F, Station 3, 2" Radius.

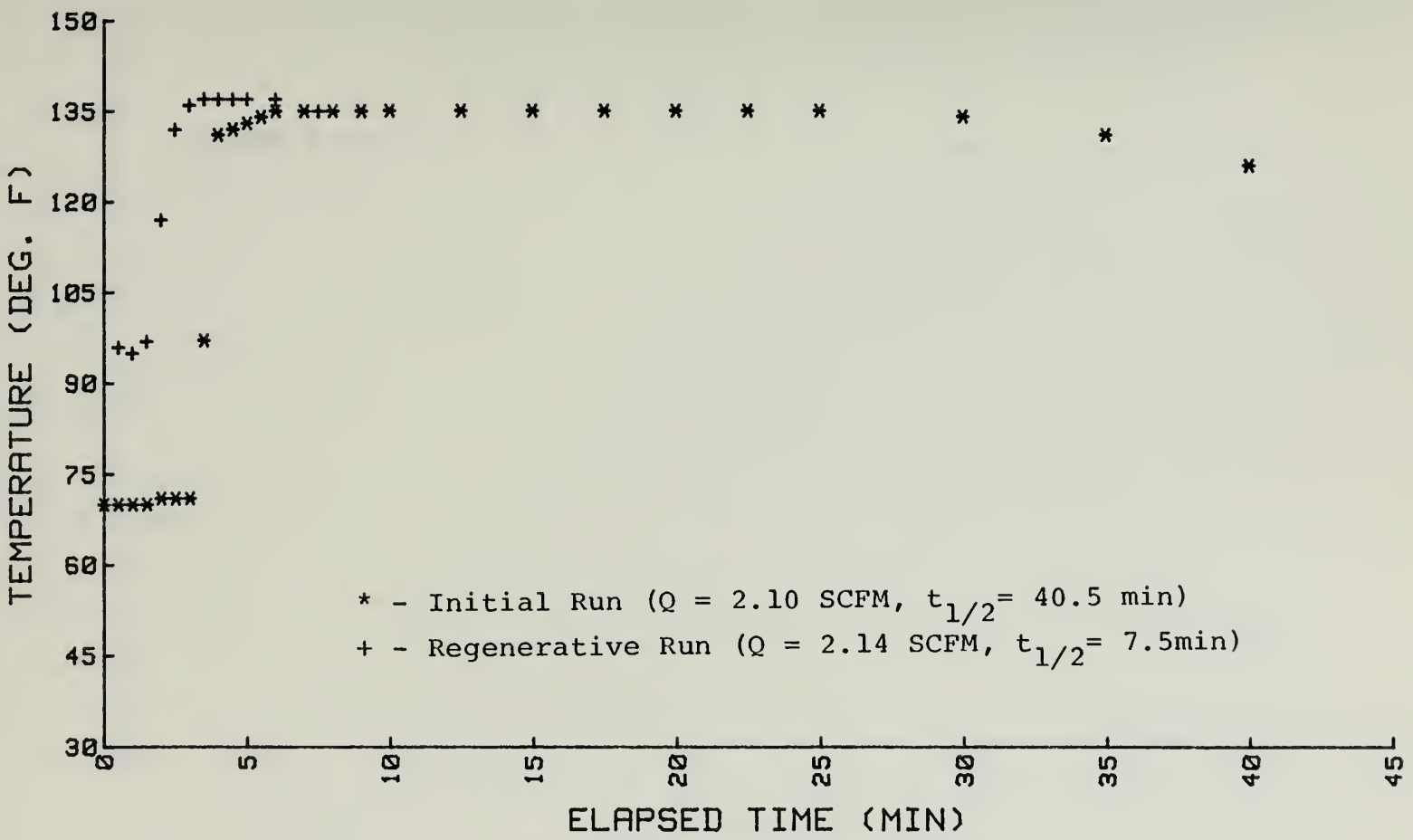


Figure 63. Comparison of Radial Temperatures between Initial and Regenerative Runs, L/D = 2.125, T = 70°F, Station 4, 0" Radius (centerline).

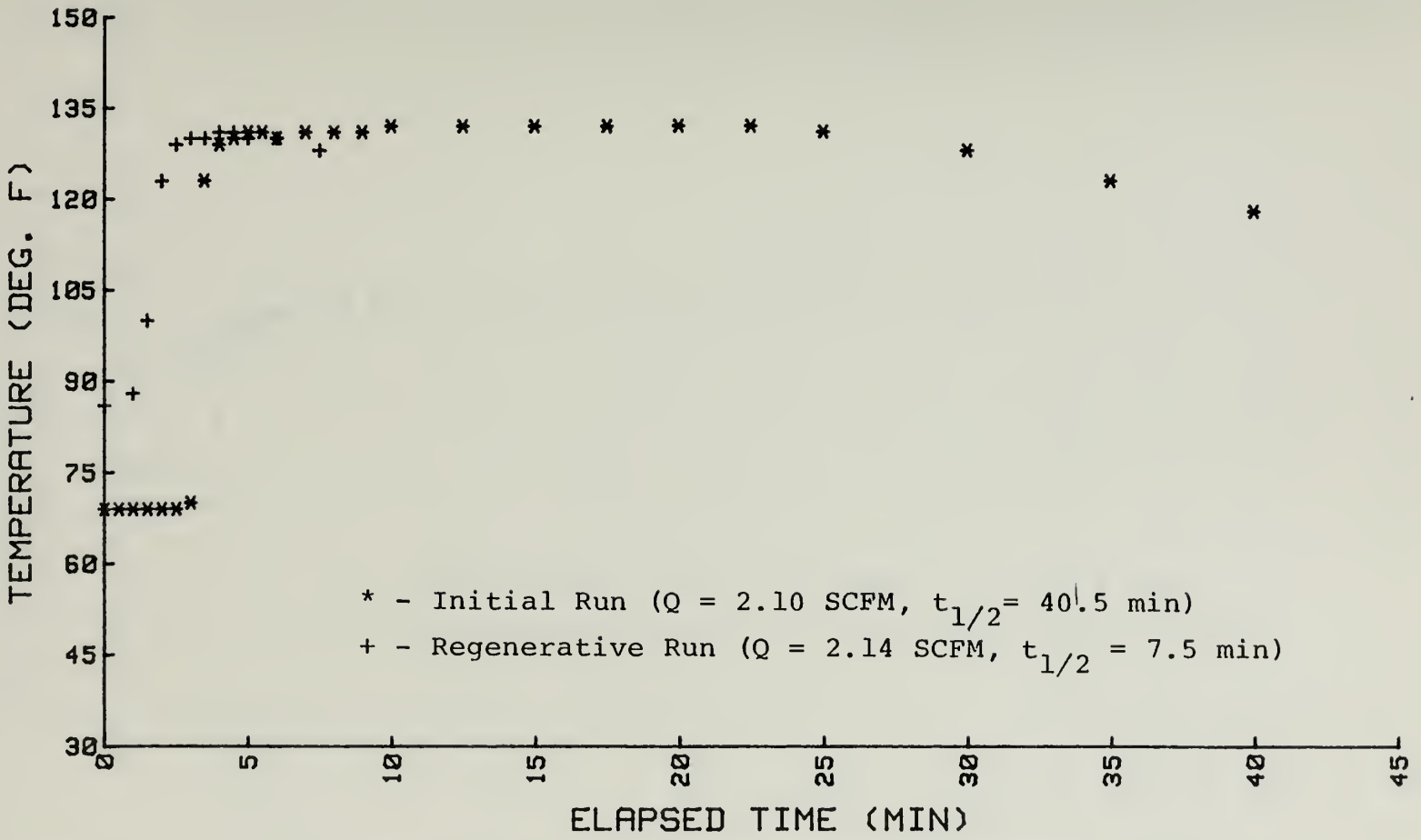


Figure 64. Comparison of Radial Temperatures between Initial and Regenerative Runs, L/D = 2.125, T = 70°F, Station 4, 1" Radius.

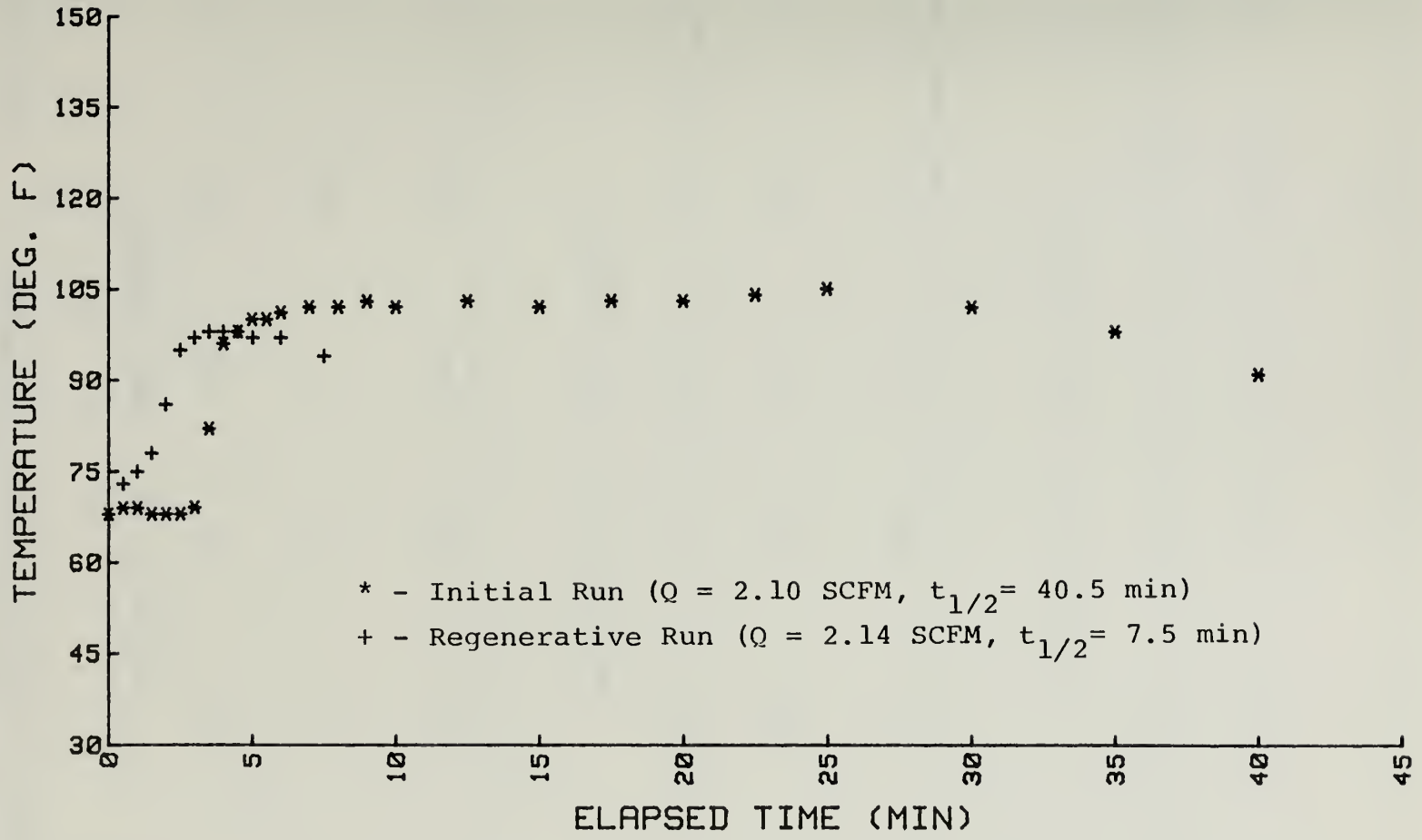
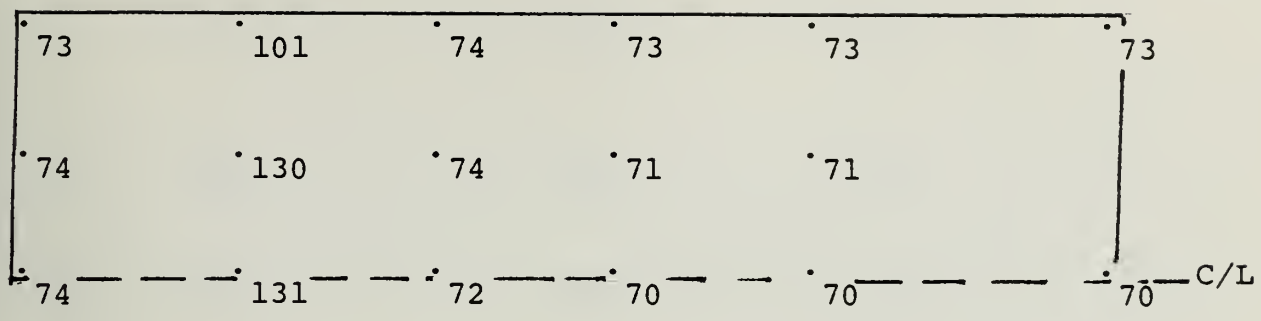
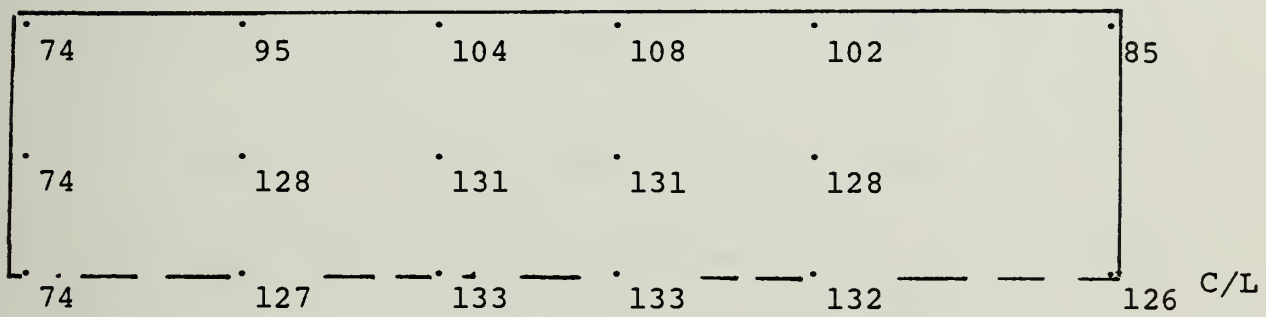


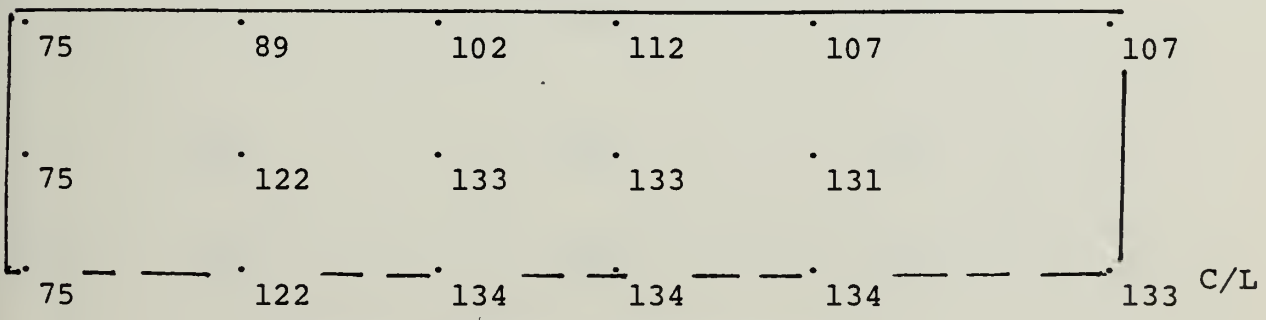
Figure 65. Comparison of Radial Temperatures between Initial and Regenerative Runs, L/D = 2.125, T = 70°F, Station 4, 2" Radius.



Elapsed Time - 2.5 minutes

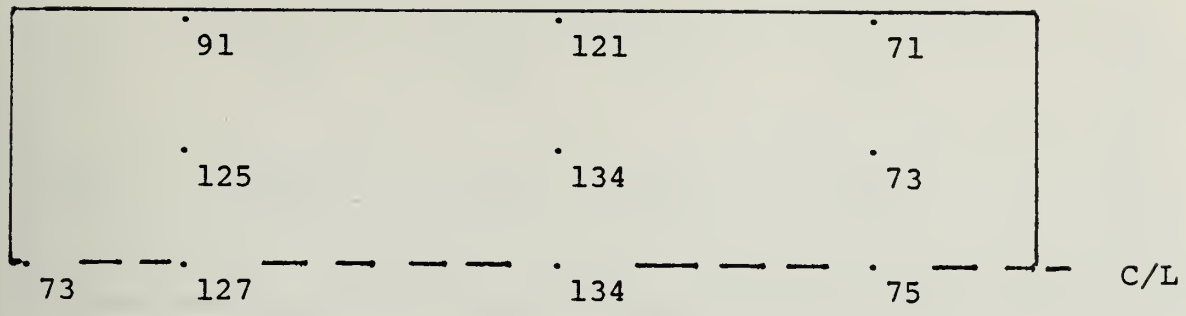


Elapsed Time - 10.0 minutes

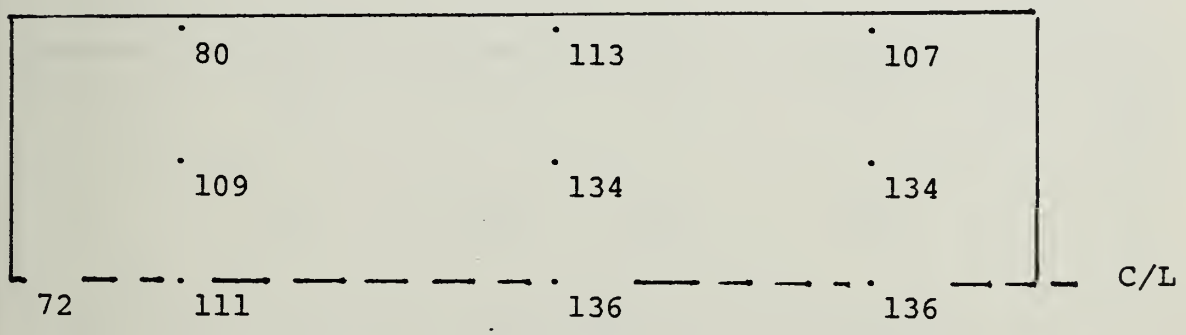


Elapsed Time - 26.5 minutes

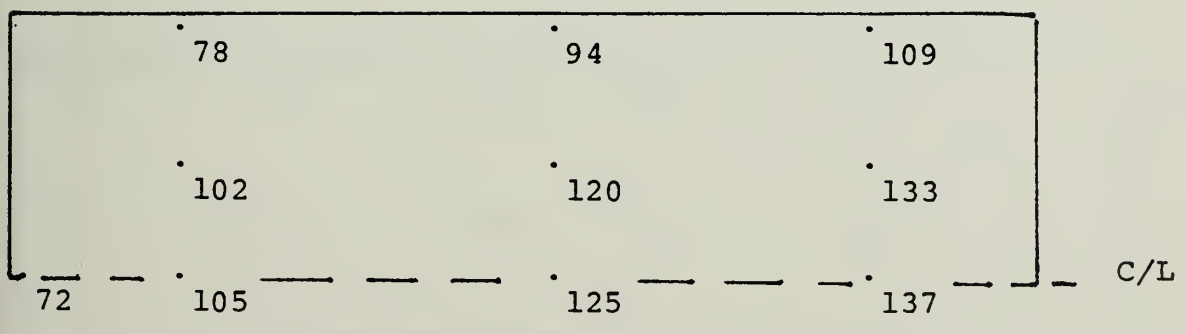
Figure 66. Sodasorb Bed Temperatures at Specified Times, L/D = 2.125, Q = 1.09 SCFM, Water Bath Temperature = 70°F.



Elapsed Time - 2.5 minutes

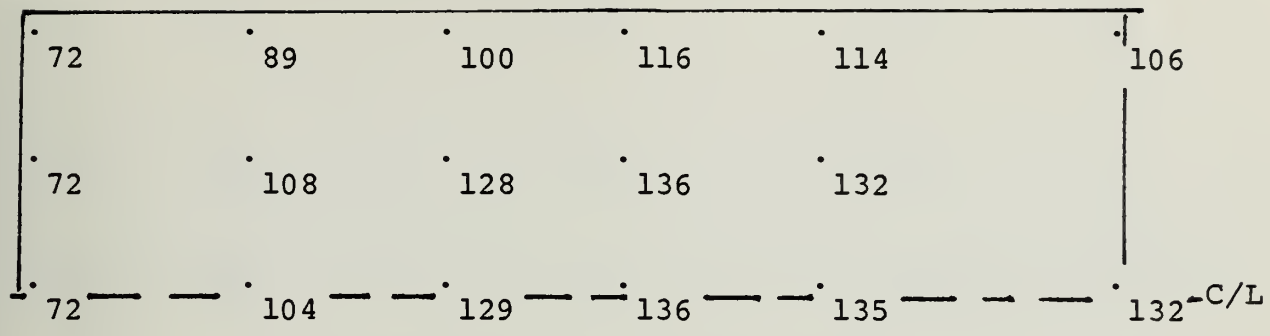


Elapsed Time - 10.0 minutes

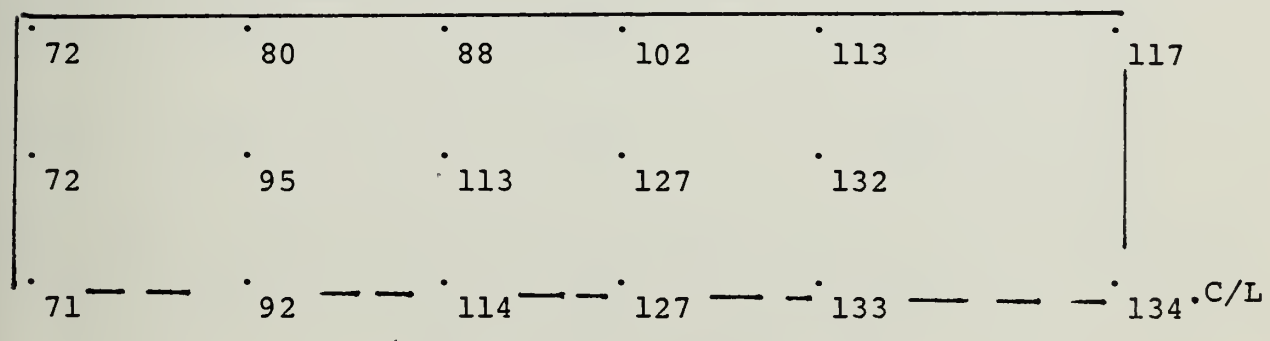


Elapsed Time - 25.0 minutes

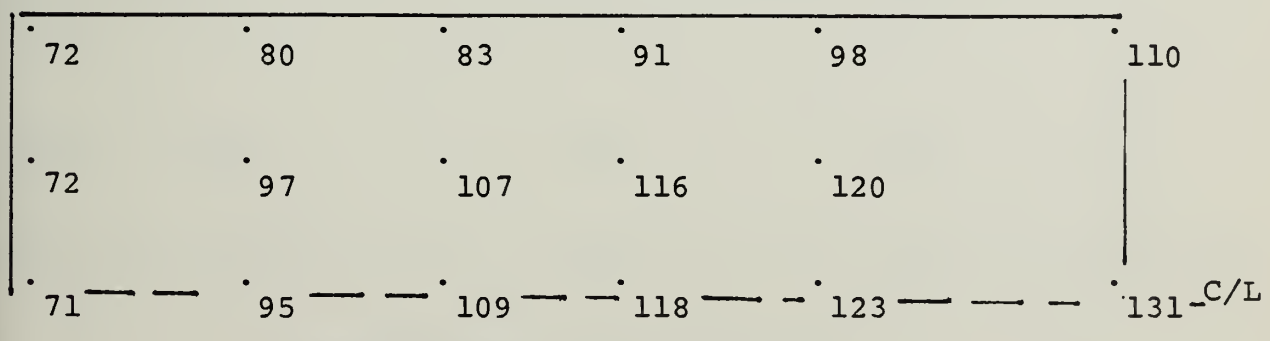
Figure 67. Sodasorb Bed Temperatures at Specified Times, L/D = 2.125, Q = 2.08 SCFM, Water Bath Temperature = 70°F.



Elapsed Time - 2.5 minutes

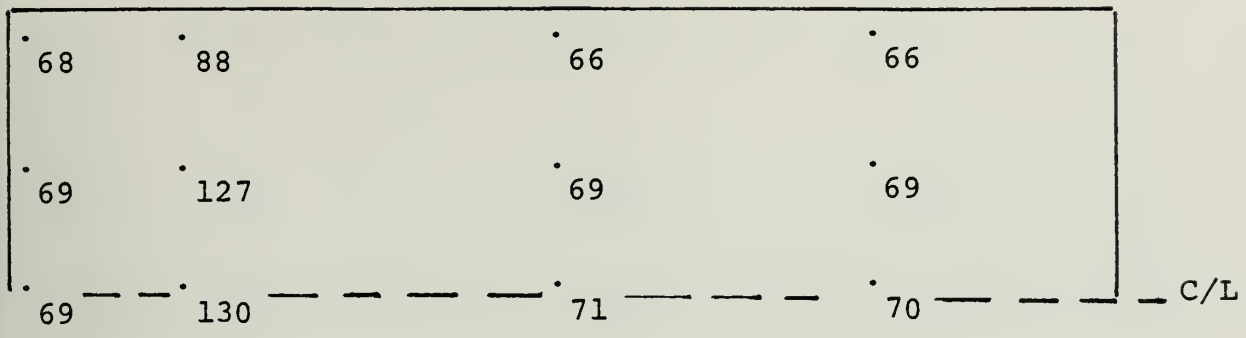


Elapsed Time - 9.5 minutes

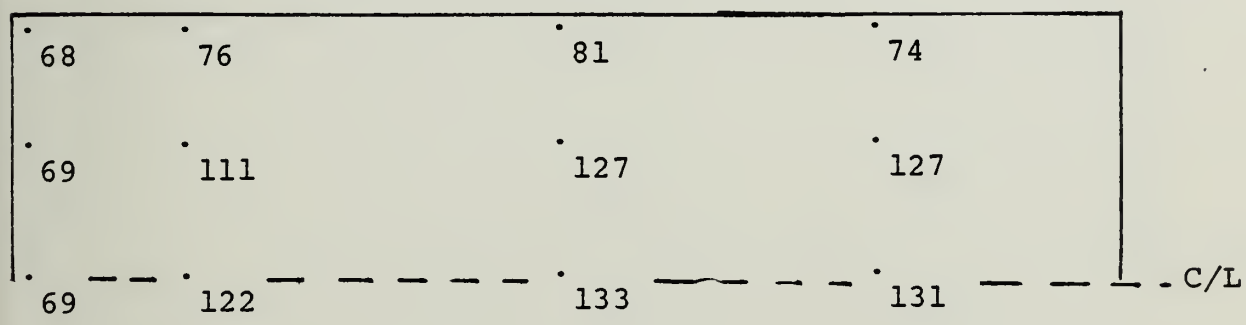


Elapsed Time - 26.5 minutes

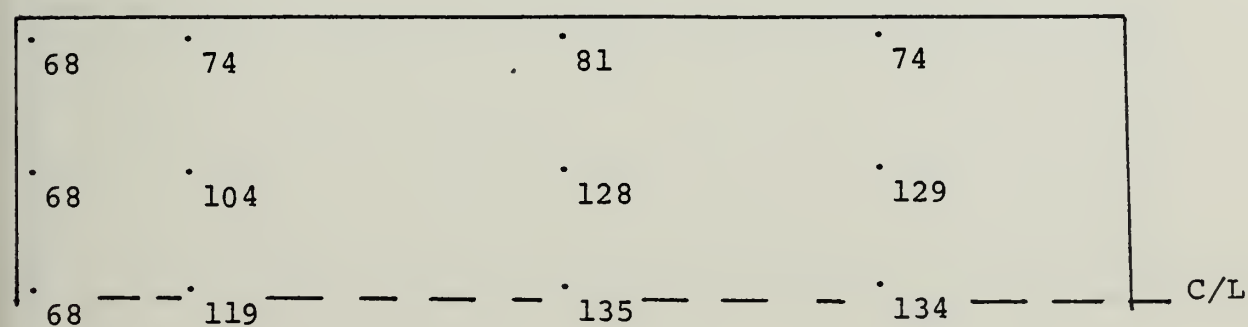
Figure 68. Sodasorb Bed Temperatures at Specified Times, L/D = 2.125, Q = 3.09 SCFM, Water Bath Temperature = 70°F.



Elapsed Time - 2.5 minutes

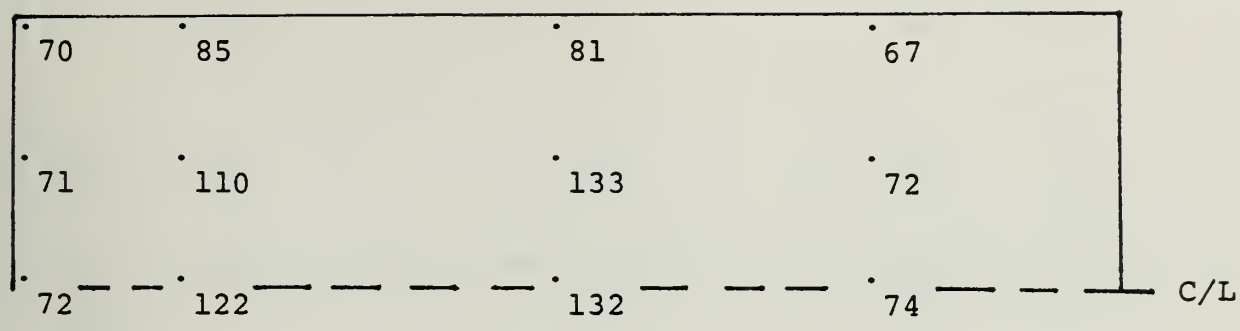


Elapsed Time - 10.0 minutes

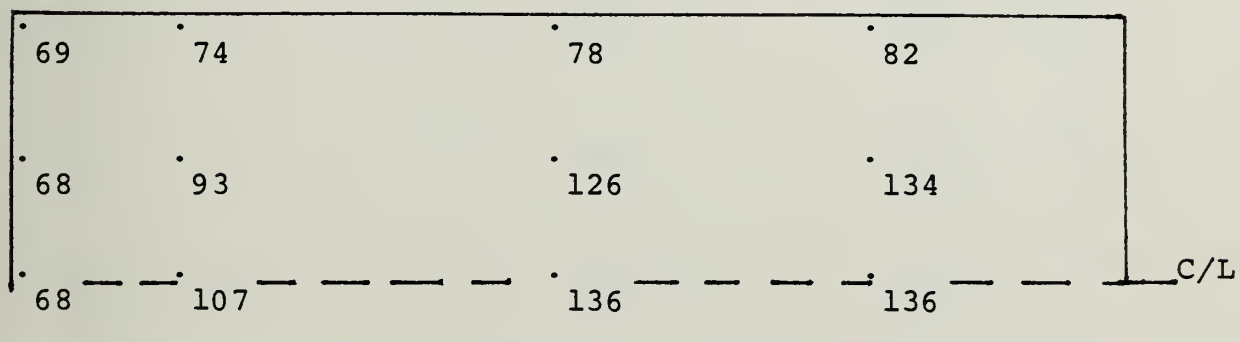


Elapsed Time - 25.0 minutes

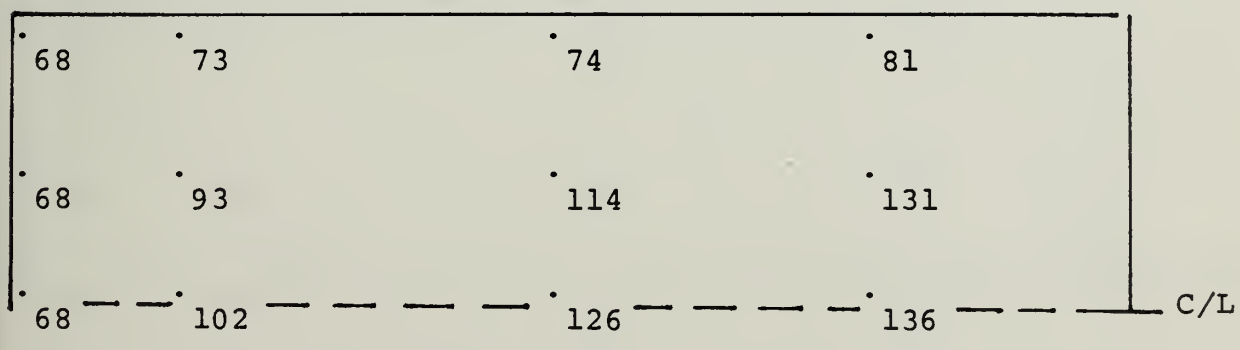
Figure 69. Sodasorb Bed Temperatures at Specified Times with Annular Rings, L/D = 2.125, Q = 1.12 SCFM, Water Bath Temperature = 70°F.



Elapsed Time - 2.5 minutes

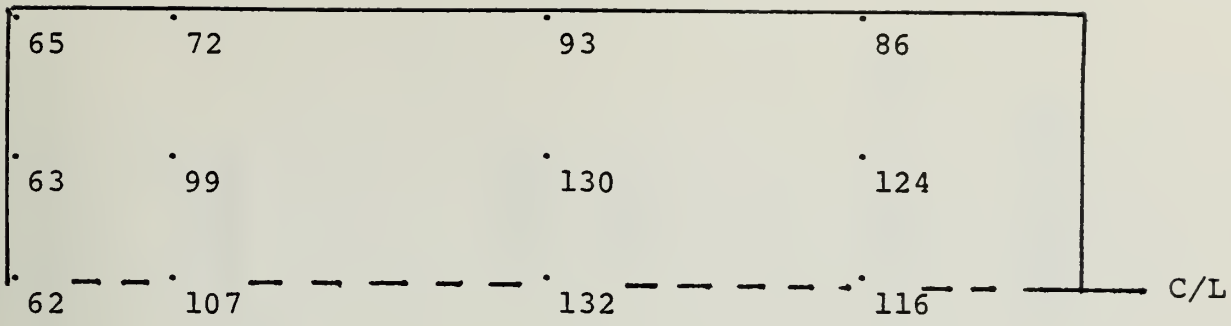


Elapsed Time - 10.0 minutes

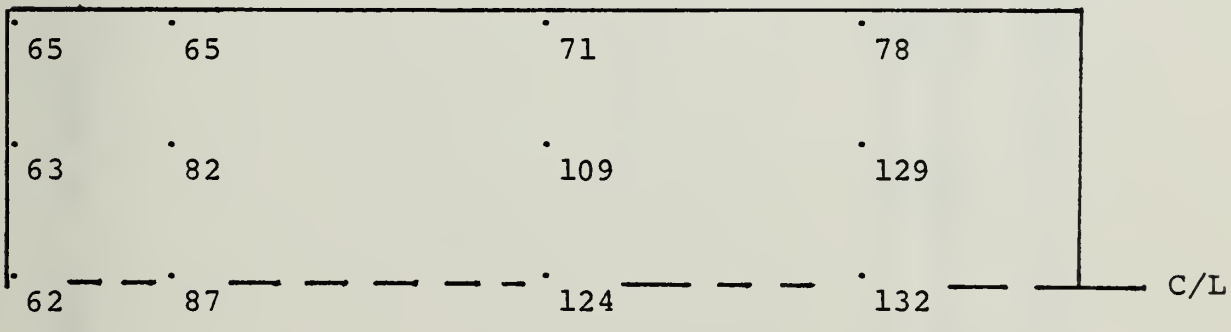


Elapsed Time - 25.0 minutes

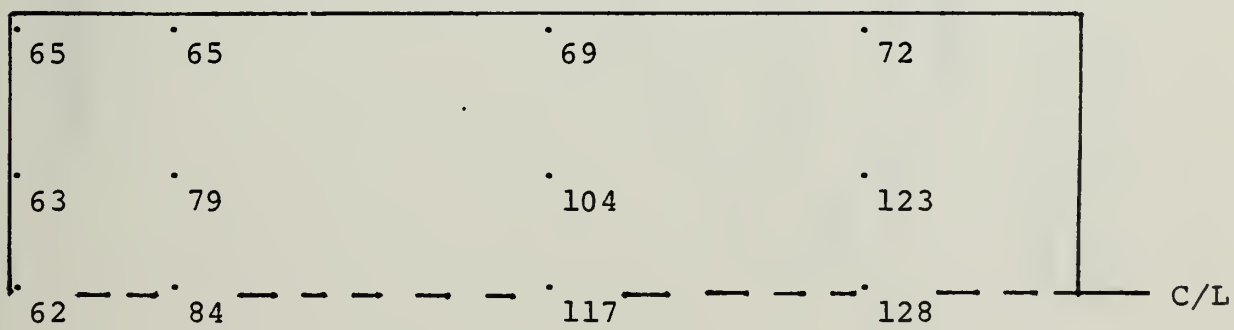
Figure 70. Sodasorb Bed Temperatures at Specified Times with Annular Rings, L/D = 2.125, Q = 2.08 SCFM, Water Bath Temperature = 70°F.



Elapsed Time - 2.5 minutes



Elapsed Time - 10.0 minutes



Elapsed Time - 19.0 minutes

Figure 71. Sodasorb Bed Temperatures at Specified Times w with Annular Rings, L/D = 2.125, Q = 3.12 SCFM, Water Bath Temperature = 70°F.

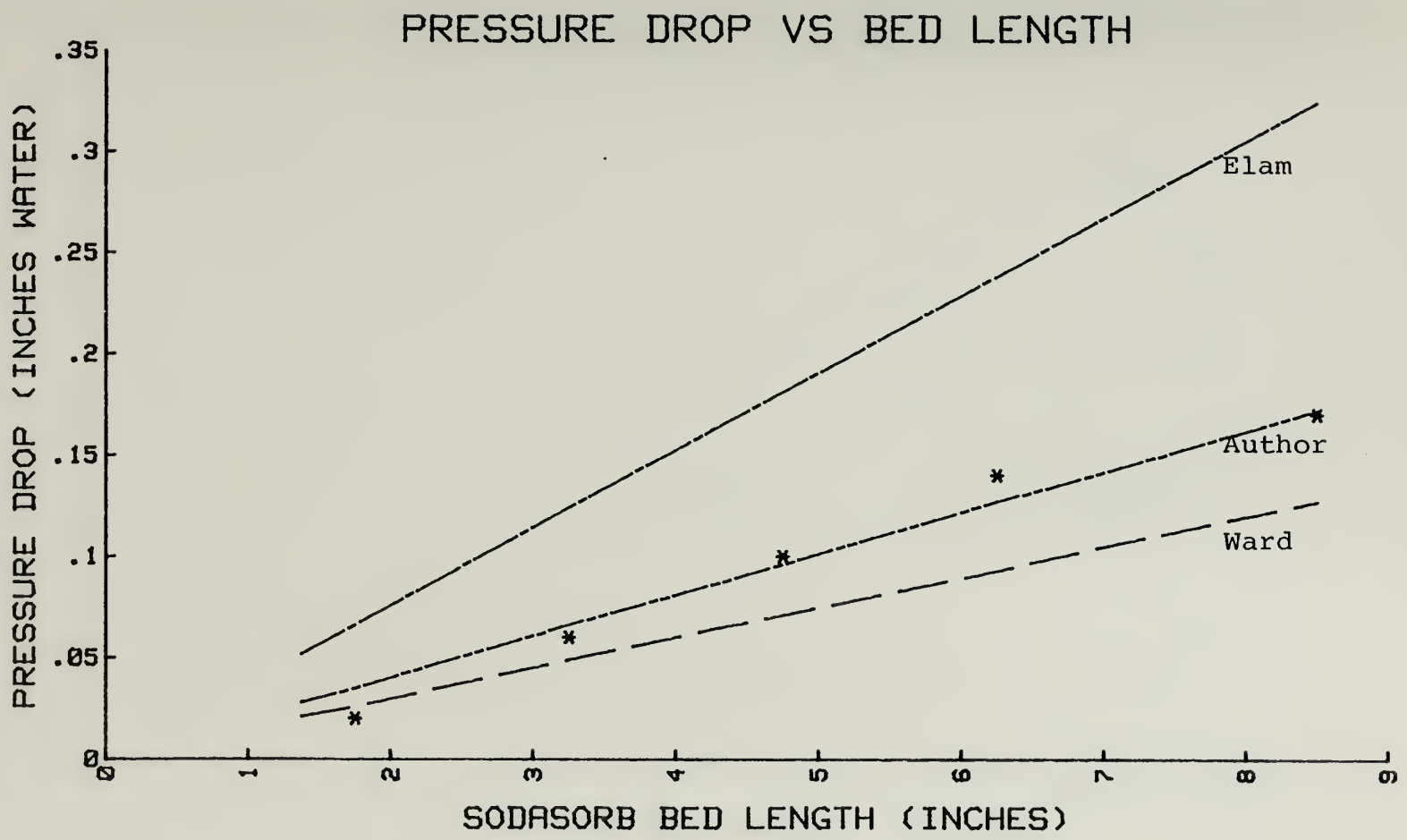


Figure 72. Pressure Drop as a Function of the Length of the Sodasorb Bed, Q = 1.09 SCFM.

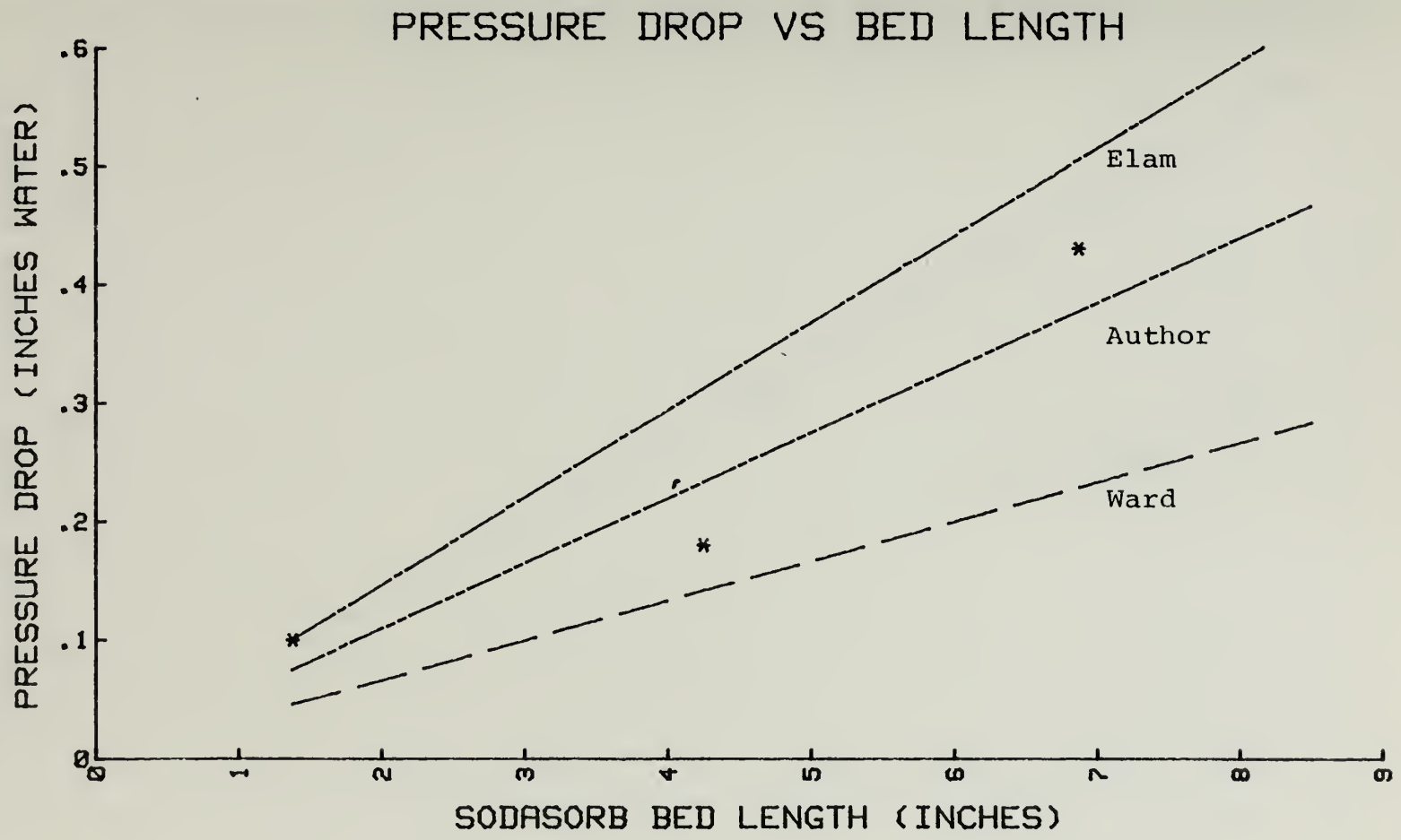


Figure 73. Pressure Drop as a Function of the Length of the Sodasorb Bed, Q = 2.10 SCFM.

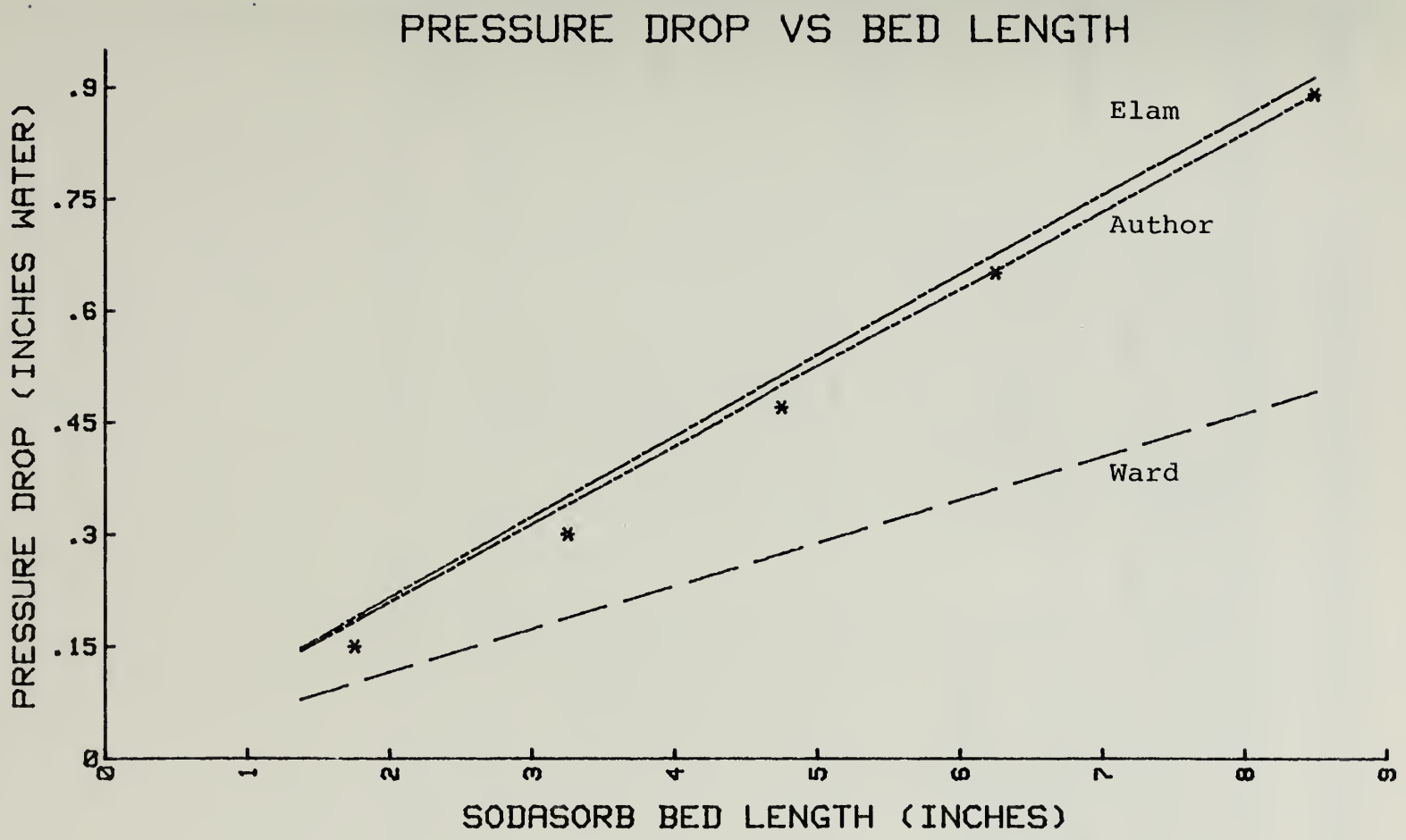


Figure 74. Pressure Drop as a Function of the Length of the Sodasorb Bed, Q = 3.09 SCFM.

APPENDIX A: NOMENCLATURE AND LOCATION OF CANISTER STATIONS

Station	Distance in inches from commencement of Sodasorb Bed			
	Variable L/D Canister	Annular Ring, Variable L/D, Canister		
	(Same for all L/D Ratios)	L/D Ratio		
		2.125	1.60	1.225
1 (entrance)				
2	1-3/4	1-3/8	1-3/8	1-3/8
3	3-1/4	4-1/4	3-7/8	3-5/8
4	4-3/4	6-7/8	6-3/8	5-7/8
5	6-1/4			
6 (exit)				

APPENDIX B: EXPERIMENTAL PROCEDURES

A. ALIGNMENT OF THE INFRARED DETECTOR

1. Warm up for 60 minutes.
2. Purge with nitrogen for five minutes.
3. RANGE to CAL, GAIN to 10XX, T A FCN switch to 100%T, SLIT to 0, check meter reading of 0.
4. SLIT to 0.5mm, WAVELENGTH to 3.5 micrometers, TIME CONSTANT to one second.
5. PATHFINDER fully counter clockwise to stops, then clockwise to 0. Adjust continuous GAIN to a meter reading of 0.6.
6. PATHFINDER fully counterclockwise to 14.26. PATHFINDER clockwise slowly to a maximum meter reading. (The PATHFINDER was consistently at 40 for a maximum meter reading on all runs.)
7. T A FCN switch to A1, SLIT to 2mm, WAVELENGTH to 4.25 micrometers.
8. By adjusting the CONTINUOUS GAIN to read from 0 to 1.0 on the meter, align the recorder to the exact same value as the meter.
9. Adjust CONTINUOUS GAIN to a meter reading of 0 while nitrogen is being purged through the infrared detector.
10. Pass 8.0% C02 through the detector. If the reading is the same as shown on the calibration chart, the

infrared detector is calibrated. If not, proceed to step 11.

NOTE: The calibration chart is a plot of infrared detector readings for given percent by volume CO2. The chart should be plotted at the beginning of the research for reference throughout the period of experimentation.

11. While passing 8.0% CO2 through the infrared detector, adjust WAVELENGTH to give the same reading as shown on the calibration chart.

NOTE: This adjustment to WAVELENGTH should be microscopic and such that the reading is still 4.25. If WAVELENGTH must be adjusted to a setting other than 4.25, it will be necessary to create a new calibration chart.

12. Purge the detector with nitrogen and, if necessary, adjust continuous GAIN to a meter reading of 0. Repeat step 10.

B. TWO HOURS PRIOR TO THE FIRST RUN OF THE DAY

1. Replace the primary Drierite dessicant in the input line to the infrared detector if the color change from blue to red is more than 50% the height of the

vertical bed of Drierite. Replace the reserve Drierite dessicant after 10 runs or at any indication of a change in color.

2. Turn on the infrared detector.
3. Zero all manometers.
4. Fill the water bath and constant-temperature refrigeration unit and provide a large siphon (a minimum of two one-inch hoses) between them to assure equal water levels.
5. Drain the water separators (to the infrared detector and in the gas supply line).
6. Fill both humidifiers with water to not more than 30% level.
7. Verify bath temperature is at appropriate temperature.
8. For the Variable L/D Canister without annular rings, position the thermocouples at the desired lengths of the canister. Check for consistent temperature readings. Wipe out inside of the canister with ethyl alcohol and thoroughly blow dry.

C. 45 MINUTES PRIOR TO RUN (If bath temperature is 70°F, otherwise conduct these steps 2 hours prior to run)

1. Shut the supply valve to the canister and open the bypass valve at the rotameter exhaust.

2. Weigh out the correct amount of Sodasorb for the desired L/D ratio to be used. For L/D ratios of 1.225, 1.60 and 2.125, use 1.80 lbs, 2.35 lbs and 3.0 lbs respectively of Sodasorb.
3. FOR THE ANNULAR RING CANISTER ONLY, select the desired number of annular rings, and the correct spacers and midsection for the desired L/D ratio. Assemble the canister in accordance with the procedures outlined in Appendix C.
4. FOR THE VARIABLE L/D CANISTER ONLY, fill the canister with fresh Sodasorb.
5. Ensure backing screws are in a position to prevent any movement in the Sodasorb. Horizontally inspect the canister to ensure that no movement of the Sodasorb takes place with mild shaking of the canister.
6. Ensure that the petcock to the Discharge Chamber is closed.
7. Place the canister horizontally in the water bath. Monitor canister for any leaks.
8. Connect the sampling tube to the sampling port on the top of the discharge chamber.

D. 30 MINUTES PRIOR TO RUN

1. Verify recorder is aligned with the infrared detector meter reading.

E. 15 MINUTES PRIOR TO RUN

1. Check the calibration of the infrared detector. (Do not continue if this is not exactly the same as the initial calibration.)
2. Establish the desired supply flow rate and volume percentage of carbon dioxide. The carbon dioxide regulator and the air supply regulator should both be at ten psig. Throttle the bypass valve to produce the pressure as expected at the flowmeter in the run. Recheck the percentage of carbon dioxide with a calibrated gas. Purge the infrared detector with pure nitrogen to a meter reading of 0. Connect the output from the canister exhaust to the infrared detector. Select and record the desired recorded speed.

F. COMMENCEMENT OF RUN

1. Record start time.
2. Open the supply valve to the canister at the rotameter exhaust.
3. Shut the bypass valve at the rotameter exhaust.
4. Ensure flow to the infrared detector.
5. Do not allow moisture, dessicant dust or any greater than atmospheric pressure at the infrared detector.

G. COMPLETION OF RUN

1. Purge the infrared detector with nitrogen until the meter reads 0.
2. Check the calibration of the infrared detector at the cutoff carbon dioxide percent and the input carbon dioxide percent. (Do NOT readjust the continuous GAIN from that of the original calibration.)
3. Measure and record the input percentage of carbon dioxide.
4. Determine to the nearest half of a minute the time ($t_{\frac{1}{2}}$) to termination of experiment.
5. Purge the infrared detector with nitrogen.
6. Secure the supply of carbon dioxide to the canister. Continue the airflow for about five minutes.
7. Secure the air supply and remove the canister from the water bath. If upon disassembly there is any moisture or caking in the Sodasorb, repeat the entire run.
8. Clean and dry all components.
9. Weigh and record the weight of the Sodasorb.
10. Replace Drierite in the infrared detector supply line.

H. CONSECUTIVE RUNS

1. If consecutive runs are desired, proceed to D.5.

APPENDIX C: ASSEMBLY OF THE ANNULAR RING CANISTER

1. As shown in Figure 8, there are five basic sections to this canister: Entrance Chamber, Entrance Canister Section, a choice of three Middle Canister Sections, Exit Canister Section, and the Discharge Chamber. Although of the same length, the Entrance and Exist Canister Sections are not interchangeable. The Exit Canister Section has an O-Ring groove in the flange; the Entrance Canister Section does not.
2. Place the Entrance Chamber vertically on end. Use the slot on top of the water bath to support the chamber.
3. Insert the connecting rods through the holes in the rim of the Entrance Chamber.
4. If an annular ring is NOT desired at the entrance of the canister, proceed to step 8.
5. If the length-to-diameter (L/D) ratio is 1.225 or 1.60, proceed to step 7.
6. Position the large outside diameter annular ring by aligning the holes in the rim with the connecting rods.
7. Fit a rubber annular ring into the rim section of a wire-mesh screen.
8. If the L/D is 1.225 or 1.60, select the appropriate size spacer. IF THE L/D IS 2.125, NO SPACER IS USED.

9. Assemble the Entrance Canister Section.

   a. Grease the appropriate size O-Ring and press it into the groove of the entrance rim of the canister section.

   b. At the entrance end of the canister section, insert first the wire-mesh screen (rim downwards) and then the spacer. Remember - NO SPACER IF L/D IS 2.125.

   c. Align the canister section in position by passing the connecting rods through the holes in the flange.

10. Grease the appropriate size O-Ring and press it into the groove of the discharge (flanged) rim of the canister section.

11. If an annular ring is not desired at the discharge rim of the Entrance Canister Section, proceed to step 15.

12. Fill the canister section with1/3 of the measured amount of Sodasorb.

13. Level the Sodasorb with the inside rim of the canister section by striking the flanged edge of the section firmly with either the heel or side of the hand. Strike downwards to avoid the canister section being inadvertently raised, resulting in a Sodasorb spill.

14. Place the annular ring in position, ensuring no voids exist between the Sodasorb and the ring or canister wall.

15. Select the appropriate Middle Canister Section based on the desired L/D canister ratio.
16. Assemble the Middle Canister Section in in accordance with the procedures outlined in steps 9a, 9c, and 10.
17. If an annular ring is NOT desired at the discharge rim of the Middle Canister Section, proceed to step 19.
18. Repeat steps 12, 13, and 14.
19. Assemble the Exit Canister Section in accordance with the procedures outlined in steps 9a, 9c, and 10.
20. If an annular ring is NOT desired at the discharge rim of the Exit Canister Section, proceed to step 22.
21. Repeat steps 12, 13, and 14. Proceed to step 23.
22. Fill the canister with the remainder of the measured amount of Sodasorb.
23. Grease the appropriate size O-Ring and press it into the groove of the Exit Canister Section flange.
24. Insert the tail-piece nozzle and spacers into the Discharge Chamber.
25. Assemble the Discharge Chamber by aligning the holes in the top and bottom flanges with the connecting rods and lowering the chamber into position.
26. Slide the connecting rods up, one at a time, until the top end procedures through the upper flange of the Discharge Chamber. Screw on a regular 3/8-inch nut,

and push the connecting rod down until the nut is resting on the upper flange.

27. Attach the elongated 3/8-inch nut to the bottom of the connecting rod.

28. When all nuts are in place on the connecting rods, tighten each elongated 3/8-inch nut finger tight. With a wrench, doing one bolt at a time and in succession, tighten each nut in half turn increments. Continue tightening until a moderate resistance is felt. Overtightening will result in failure of one or more of the glued flange joints on the canister sections.

29. Visually inspect to ensure that all O-Rings are in place and that all sections are properly aligned and snubbed down.

APPENDIX D: CALCULATION OF THE STANDARD VOLUMETRIC FLOW RATE

The standard volumetric flow rate was calculated in accordance with Equation B-11 contained in reference [3]:

$$Q_s = Q_f \sqrt{\frac{P_f}{P_s} \frac{T_s}{T_f}} \qquad \left(\frac{ft^3}{min}\right) \qquad \text{(D-1)}$$

where

$T_s = 530\ (^{o}R)$

$P_s = 14.7\ (psia)$

The volume percentage input of carbon dioxide was measured and the time ($t_{\frac{1}{2}}$) for 0.5% carbon dioxide by volume in the exhaust from the canister was experimentally determined.

APPENDIX E: EXPERIMENTAL UNCERTAINTY ANALYSIS

The sources of error in the results presented are due to instrument precision and accuracy, and inaccuracies in geometrical measurements. Instrumentation errors occurred in measuring flow rate, temperature, pressure, volume percentage of carbon dioxide in the gas and time for the exhaust gas to reach 0.5% by volume carbon dioxide. The following uncertainties were estimated:

P_{atm}:	negligible	
P_L :	.5 $\pm$ .005 inches of water	$\pm$ 1.0%
P_f :	15 $\pm$ .05 psia	$\pm$ 0.3%
P_c :	15 $\pm$ .02 psia	$\pm$ 0.1%
CO_2 :	.06 $\pm$ .001	$\pm$ 1.7%
$t_{½}$:	30 $\pm$ .25 minutes	$\pm$ 0.8%
T :	530 $\pm$ 2 ^{o}R	$\pm$ 0.4%
Q_f :	2.00 $\pm$ .046 ft^3/min	$\pm$ 2.3%

The uncertainties in geometrical measurements were:

L :	6.40 $\pm$ .1 inches	$\pm$ 1.6%
D :	4.00 $\pm$ .02 inches	$\pm$ 0.5%

APPENDIX F: SAMPLE CALCULATIONS OF SODASORB MASS AND EFFICIENCY RATIOS

Table VIII is a comparison effectiveness of Sodasorb for a given mass of Sodasorb for an approximate volumetric flow rate. Figures 22, 23 and 24 are plots of the data contained in Table VIII and show Sodasorb's effectiveness as a function of mass for a given volumetric flow rate. Figures 25, 26 and 27 are plots of Sodasorb's effectiveness vs mass for a given environmental temperature. The Sodasorb mass ratios and effectiveness ratios shown in Table VIII were calculated as follows:

Example: 1) $\frac{M_{(\ )}}{M_{2.215}}$: Mass Sodasorb = $\rho \cdot (\text{vol})$

$= \rho \frac{\pi}{4} D^2 L$

$$\frac{M_{1.60}}{M_{2.125}} = \frac{\rho \frac{\pi}{4} D^2 (1.60D)}{\rho \frac{\pi}{4} D^2 (2.124D)} = \frac{1.60}{2.125} \simeq .753$$

$$\frac{M_{1.225}}{M_{2.125}} = \frac{1.225}{2.125} = 0.576$$

2) $\frac{t_{1/2\ (\quad)}}{t_{1/2\ (2.125)}}$ for test run #36

$$\frac{t_{1/2\ (1.60)}}{t_{1/2\ (2.125}} = \frac{53.5}{83.5} = .641$$

$T = 55^{\circ}F$

APPENDIX G: SAMPLE CALCULATIONS FOR THE PRESSURE DROP ACROSS THE CANISTER

Given: Test Run R-1

$Q = 1.10$ SCFM $\quad D = 4$ in. $\quad dx = 8.5$ in $\quad T_{AVG} = 121.1^{\circ}F$

$A_c = \frac{\pi}{4}(4)^2$ inches $= 4 \cdot \pi$ in^2

$T = 460 + 121.^{\circ} = 581.1^{\circ}R$

Solution

from Equation (2): $-\frac{dP}{dx} = \frac{f \rho V_c^2}{\sqrt{\kappa}} \Rightarrow -dP = \left(\frac{f \rho V_c^2}{\sqrt{\kappa}}\right) dx$ (G-1)

from Reynold and Perkins [14]

$$R = 53.34 \ \frac{\text{ft-lb}}{\text{lb}_m\text{-}^{\circ}R}$$

$$\mu = .04717 \ \frac{\text{lbm}}{\text{ft-hr}} \quad \text{(interpolating @ } T = 121^{\circ}F\text{)}$$

$$P = (29.95 + 1.588) \ \text{"Hg} \times 0.4898 \ \frac{\text{lbf}}{\text{in}^2\text{-"Hg}} = 15.45 \ \frac{\text{lbf}}{\text{in}^2}$$

$$\rho = \frac{P}{RT} = \frac{(15.45 \ \frac{\text{lbf}}{\text{in}^2})(144 \ \frac{\text{in}^2}{\text{ft}^2})}{(53.34 \ \frac{\text{ft-lb}}{\text{lb}_m\text{-}^{\circ}R})(581.1^{\circ}R)} = 0.0718 \ \frac{\text{lbm}}{\text{ft}^3}$$

$$V_c = \frac{(1.10 \ \frac{\text{ft}^3}{\text{min}})(144 \ \frac{\text{in}^2}{\text{ft}^2})}{4 \cdot \pi \ \text{in}^2} = 12.605 \ \frac{\text{ft}}{\text{min}}$$

$$\frac{\rho V_c}{\mu} = \frac{(0.0718 \ \frac{\text{lbm}}{\text{ft}^3})(12.605 \ \frac{\text{ft}}{\text{min}})(60 \ \frac{\text{min}}{\text{hr}})}{.04717 \ \frac{\text{lbm}}{\text{ft-hr}}} = 1551.21 \ \frac{1}{\text{ft}}$$

from Equation (4):

$$Re = \frac{\rho V_c}{\mu}\sqrt{\kappa} = \frac{(1151.21\ \frac{1}{ft})\ (.004\ in)}{12\ \frac{in}{ft}} = 0.38373$$

from Equation (3):

$$f = \frac{1}{Re} + 1.67 = 4.2760$$

$$-dP = \frac{(4.276)(.0718\ \frac{lbm}{ft^3})\ (12.605\ \frac{ft}{min})^2\ (8.50\ in)}{(144\ \frac{in^2}{ft^2})\ (.004\ in)\ (60\ \frac{sec}{min})^2 (36.16\ \frac{ft\text{-}lbm}{lb_f\text{-}sec^2})}$$

$$dP = -.006218\ \frac{lbf}{in^2}$$

$$1\ "H_2O = .036086\ \frac{lbf}{in^2}$$

substitution into Equation (G-1):

$$dP = \frac{-.006218}{.036086\ \frac{\frac{lbf}{in^2}}{"H_2O}} = -.172\ "H_2O$$

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